Advances in Laser/Lidar Technologies for NASA's Science and Exploration Mission's Applications

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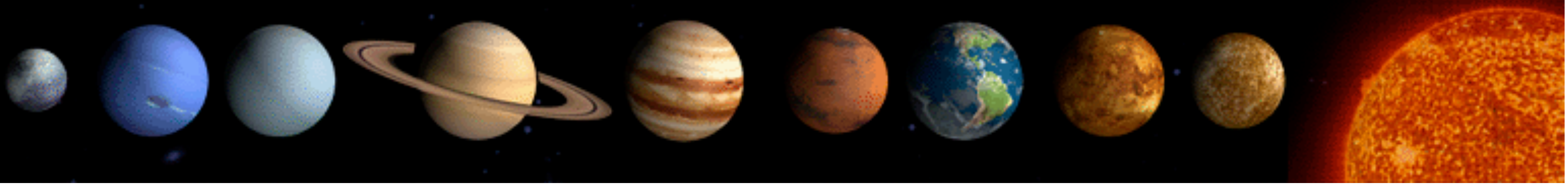


LRRP & LLTE Program Origins

- Earth Science Independent Laser Review Panel
  - Steven Alejandro (chair), Mike Hardesty, John Hicks, Dennis Killinger, Marshall Lapp
  - Project Reviews: Sept. 7-8, 2000 & Final Report: Nov. 27, 2000
  - Prepare for lidar missions before the mission & maintain in-house capability, do science-technology trade-offs, test engineering flight models in final configuration
- Integrated NASA Lidar Systems Strategy Team (INLSST)
  - Upendra Singh and Bill Heaps, co-chairs
  - Presented recommendations to Center Directors, AAs, and Administrator (6/01)
- NASA Administrator Mandated Formulation Of An Agency-level Lidar Technology Development Plan
  - Laser Risk Reduction Program (LRRP) was established and initiated in FY02
  - Co-funded by ESE/Earth Science Techology Office (ESTO) and Code R Enabling Concepts and Technologies (ECT) program
- Applied LRRP Technologies to Vision for Space Exploration (VSE) (1/14/04)
  - SMD/ESTO continued LRRP and Exploration Systems Mission Directorate funded LLTE beginning FY05

Pulsed Lidar Space Missions: History

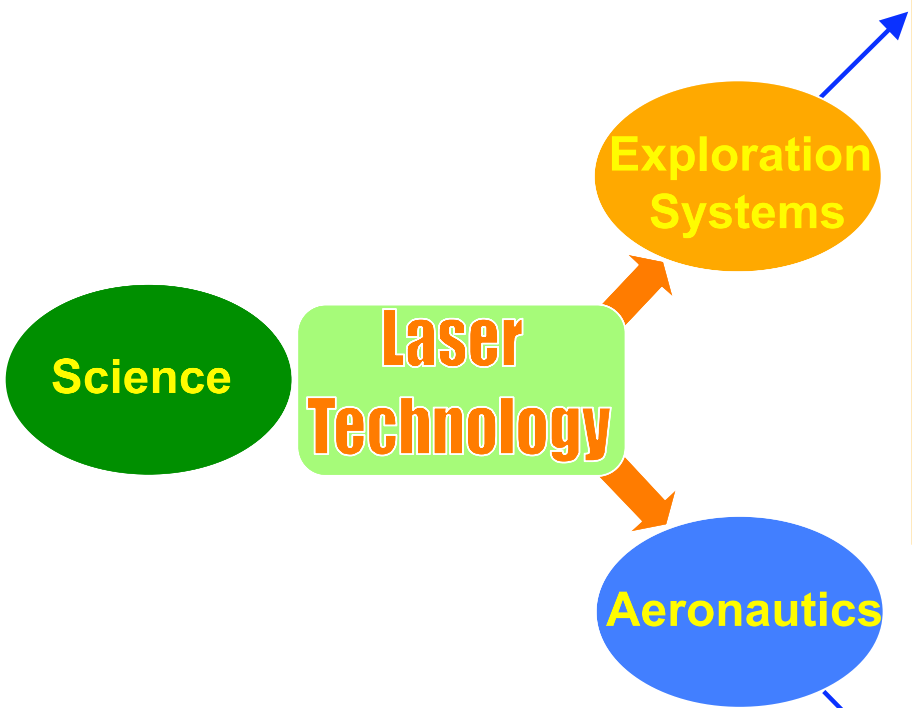
Mission	Launch	Type	Status
Apollo 15, 16, 17	1971-2	Ranging, Moon	Success
MOLA I	1992	Ranging, Mars	S/C Lost (Contamination)
Clementine	1994	Ranging, Moon	Success (BMDO/NASA)
LITE	1994	Profiling, Shuttle	Success (Energy Decline by 30%)
Balkan	*1995*	*Profiling*	*Success (Russia)*
NEAR	1996	Ranging	Success
SLA-01	1996	Ranging, Shuttle	Success
MOLA II	1996	Ranging	Success (Bar dropouts)
SLA-02	1997	Ranging, Shuttle	Success
MPL/DS2	1999	Ranging	S/C Lost
VCL	2000	Ranging	Cancelled
SPARCLE/EO-2	2001	Profiling, Shuttle	Cancelled
Icesat/GLAS	2003	Ranging+Profiling	Laser 1, 2, 3 Anomalies
Messenger/MLA	2004	Profiling, Mercury	Cost/Schedule Slips (Arr 2007)
Calipso	2005	Profiling	
ADM	*2007*	*Wind Demo. (ESA)*	*Was 2006*
LOLA/LRO	2008	Altimeter, Moon	
Mars Smart Lander	2009	Ranging, Mars	

*

Active Sensing is a Multi-Enterprise Need

Clouds/Aerosols
Tropospheric Winds
Ozone
Carbon Dioxide
Biomass Burning
Water Vapor
Surface Mapping
Laser Altimetry
Oceanography
Surface Materials
And Physical State
Surface Topography
Molecular Species
(H_2O, CO_2, Methane)

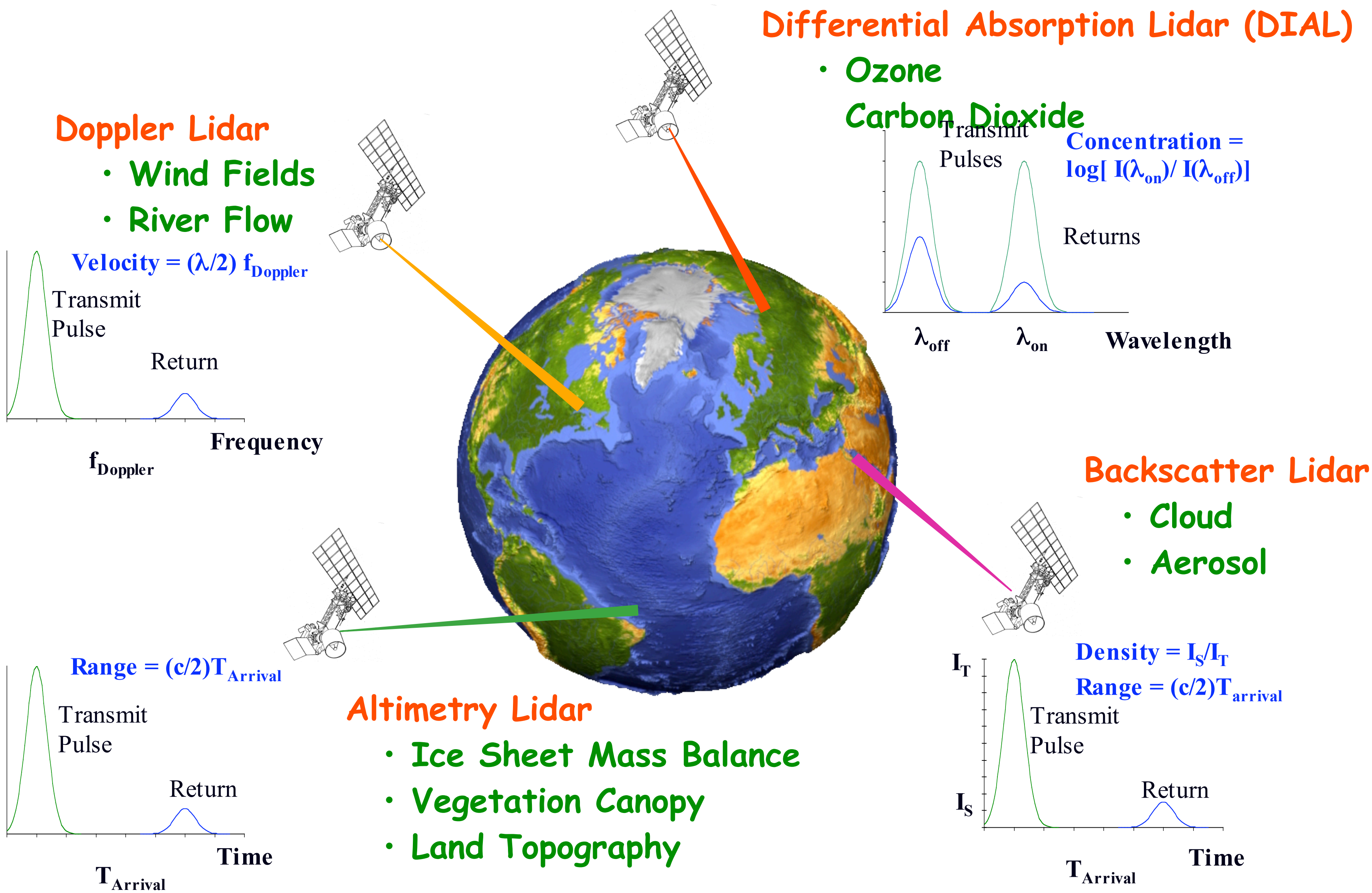
NASA Enterprises Needs



Lander Guidance/ Control
Lander Hazardous Winds/Dust Avoidance
Mars Atmospheric Winds
Biological Elements (C, N, H, S, P)
Optical Communication
Spacecraft Automatic Rendezvous/Capture
Wind Profiling for Launch Vehicles

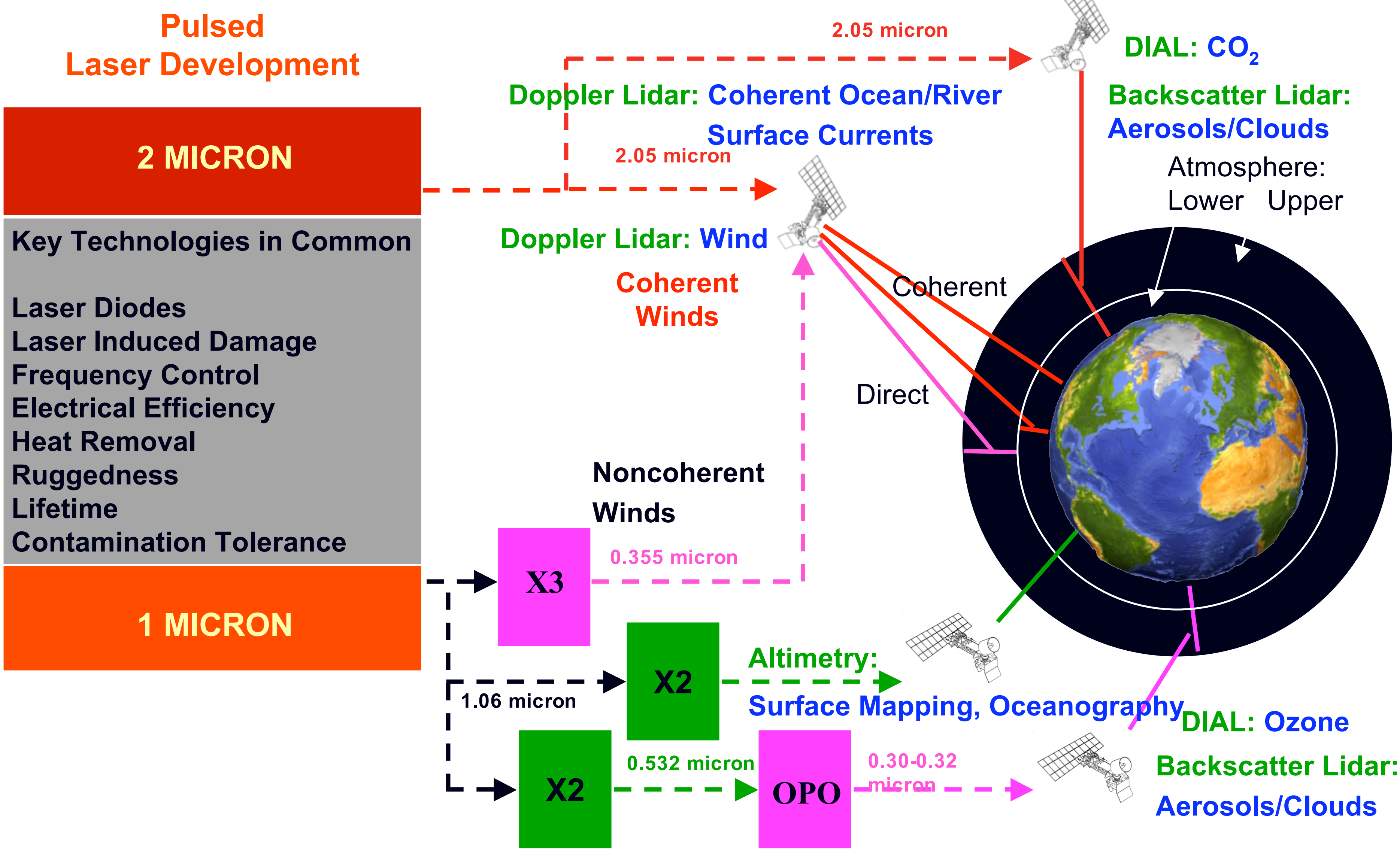
Turbulence detection
Wind shear detection
Wake vortices

Active Optical Sensing and Measurements



Earth Sciences Application Foci

2 Lasers, 4 Techniques, 6 Priority Measurements



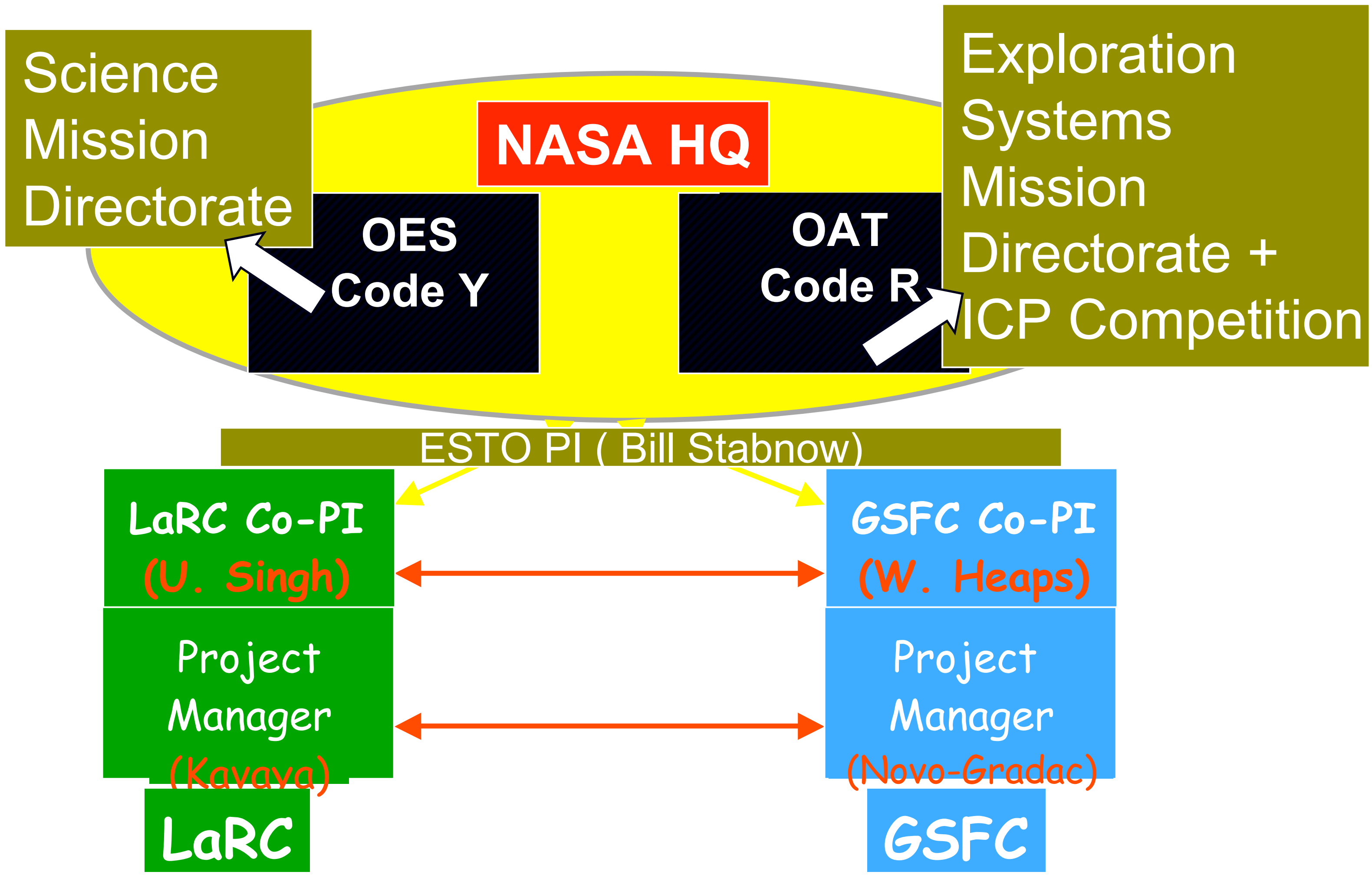
INLSST Recommendations

- Establishing Space-hardened Laser Transmitter Test Beds (1μm laser at GSFC & 2μm at LaRC)

- Development and Qualifications of Space-based Laser Diode Arrays (808nm diodes at GSFC & 792nm at LaRC)

- Advancing Wavelength Conversion Technology for Space-based Lidars (Low Energy/HRT at GSFC & High Energy/LRT at LaRC)

LRRP/LLTE - Management Model



LRRP Application Driven Elements at LaRC

- **2-micron laser transmitter**
  - Demonstrate technologies leading to a conductively cooled, diode-pumped 2-micron laser suitable for space-based lidar application
  - Address major laser development issues: high energy, high efficiency, laser-induced optical and thermal damage, system thermal management
- **High-power diode laser pump arrays**
  - Develop, scale, and qualify long-lived, space-compatible laser diode arrays with current vendors
  - Evaluate currently available laser diode arrays for performance, life and configuration required for future space-based laser missions
  - Establish Characterization and Lifetime Test Facility to address laser diode issues:
    - Limited reliability and lifetime
    - Lack of statistical and analytical bases for performance and lifetime prediction
  - Conceive advanced laser diode array architectures with improved efficiency and thermal characteristics
- **Nonlinear optics research for space-based ozone DIAL**
  - Spectrally narrow, tunable, robust UV laser architectures
  - Develop long-lived, efficient, space-compatible, nonlinear optical materials/techniques
- **Receiver technologies**
  - Develop integrated heterodyne receiver to demonstrate 3-dB improvement of coherent lidar system efficiency with 80% reduction of required local oscillator power
  - Develop improved quantum efficiency photon-counting detectors at 2 micron
- **Laser physics and advanced materials research**
  - Develop line tunable diode-pumped Nd laser system for pumping nonlinear UV generation

LaRC Task Leads, FY05

Many Thanks To:

2-Micron Pulsed Laser Transmitter, Dr. Jirong Yu

- 2-Micron Testbed
  - Compact 2-Micron Laser
  - Amplifier Development
  - Phase Conjugate Mirror
- Tm Fiber Pumped Ho Laser
- Radiation and Contamination Mitigation

Mars Orbiter Lidar, Dr. Grady J. Koch

Long-Pulse Laser Diode Arrays, Dr. Farzin Amzajerdian

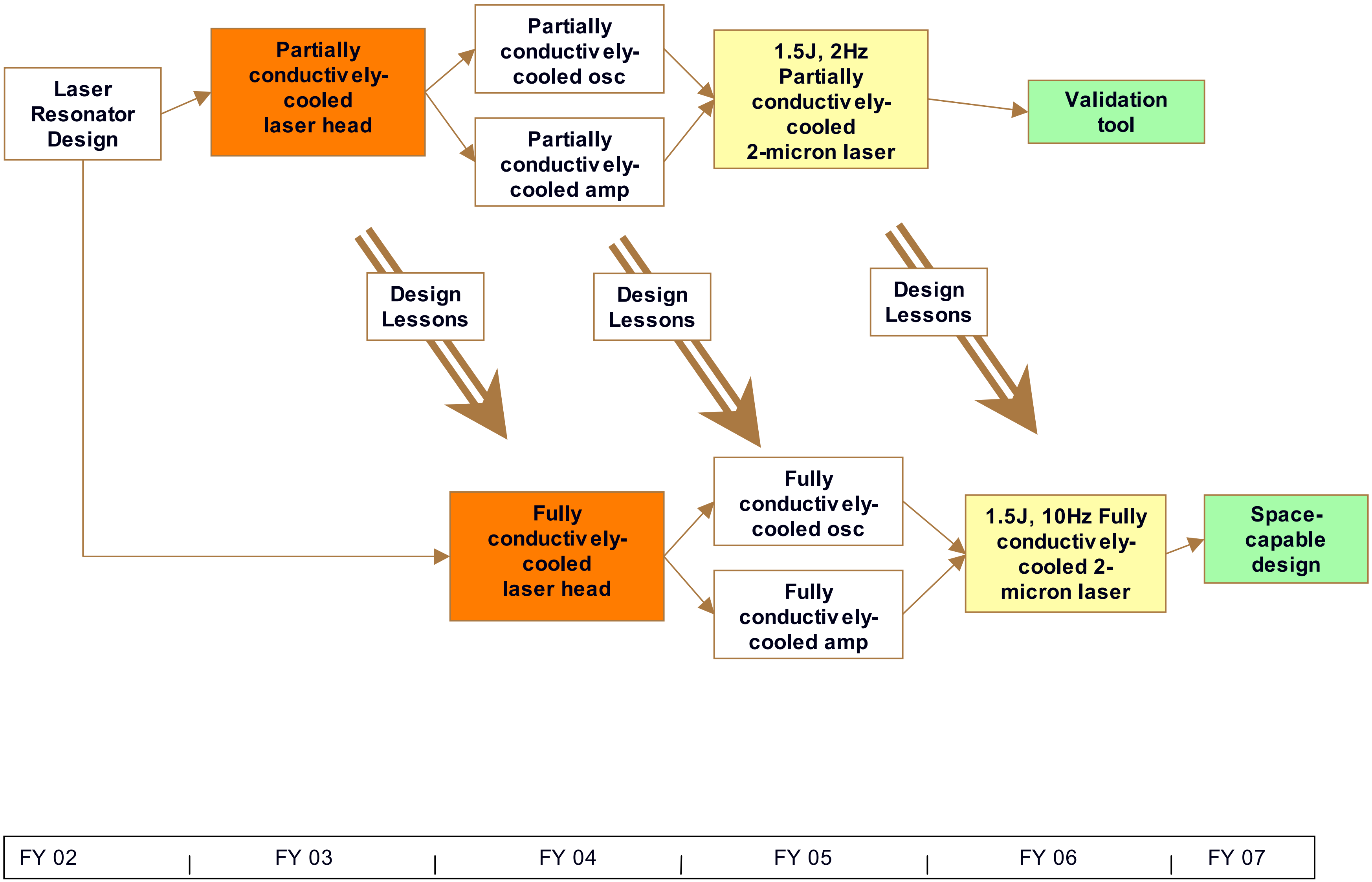
- Charactization and Qualification
- Technology Advancement Addressing Reliability Issues

UV Wavelength Conversion Technologies from 1 Micron, Dr. Narasimha Prasad

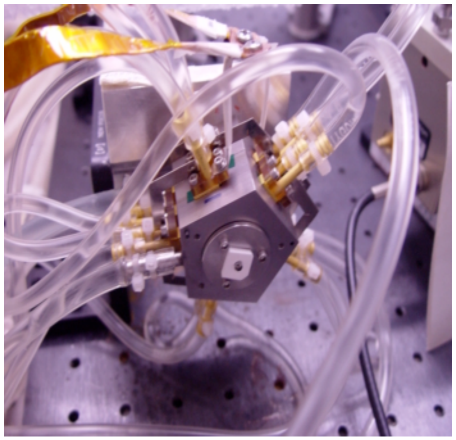
Detector Development for 2-Micron Direct DIAL, Dr. Nurul Abedin

Advanced Receiver for 2-Micron Coherent Doppler Lidar, Dr. Farzin Amzajerdian

Laser Risk Reduction Program
2-micron Technology Roadmap



2-Micron Laser Head Design Advancement

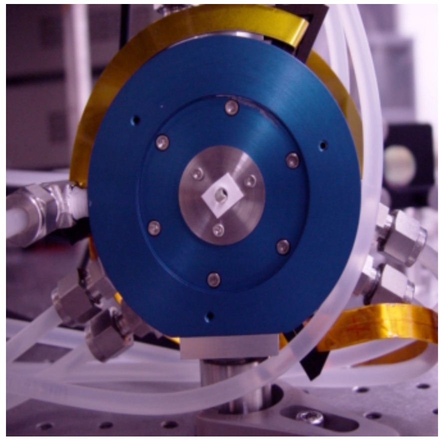


1995

10 diode arrays with total pump energy 3.6 Joules

22 water channels

All liquid cooled

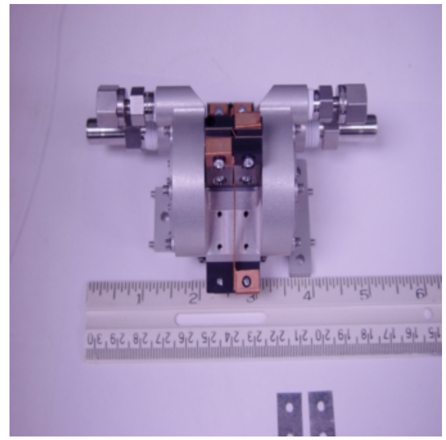


2002

6 diode arrays with total pump energy 3.6 Joules

8 water channels

LDAs cond. cooled



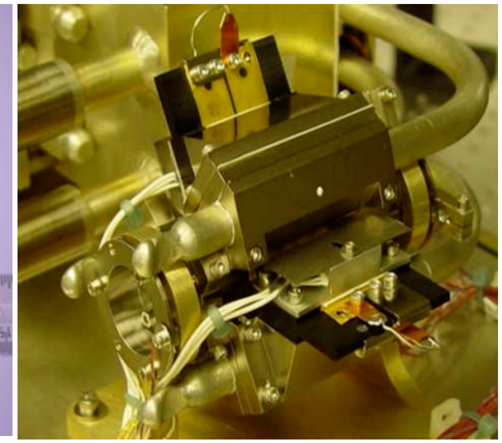
2003

6 diode arrays with total pump energy 3.6 Joules

4 water channels

LDAs cond. cooled

Monolithic design

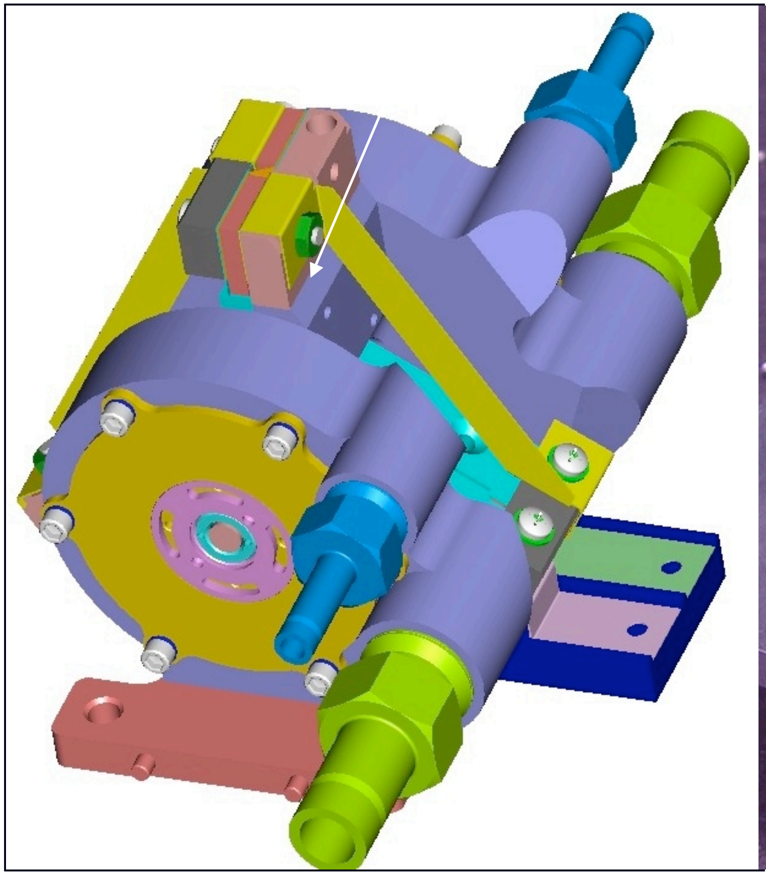


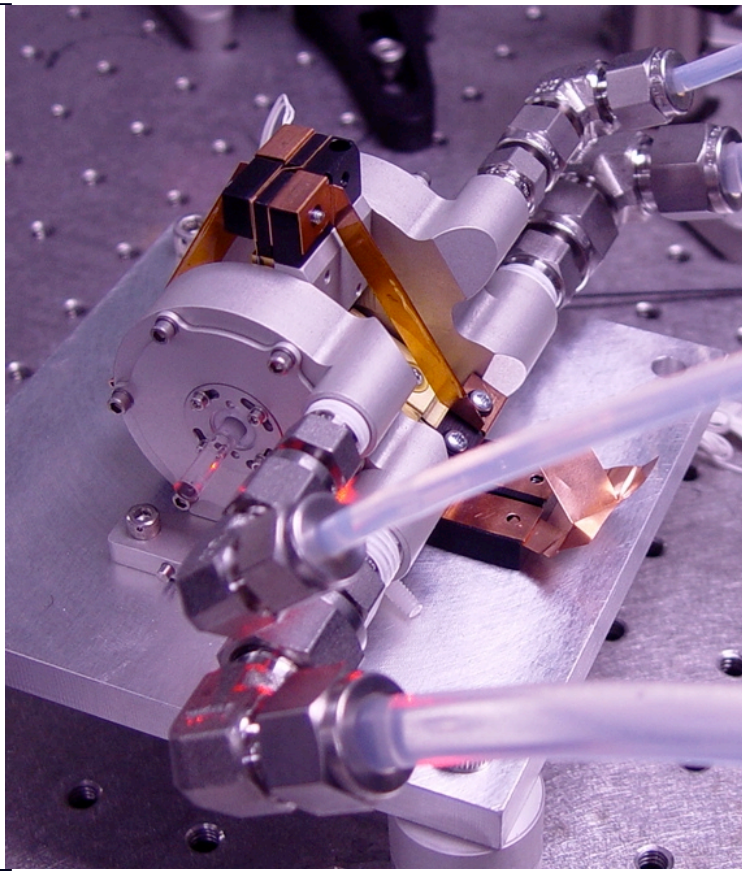
2004

6 diode arrays with total pump energy 3.6 Joules

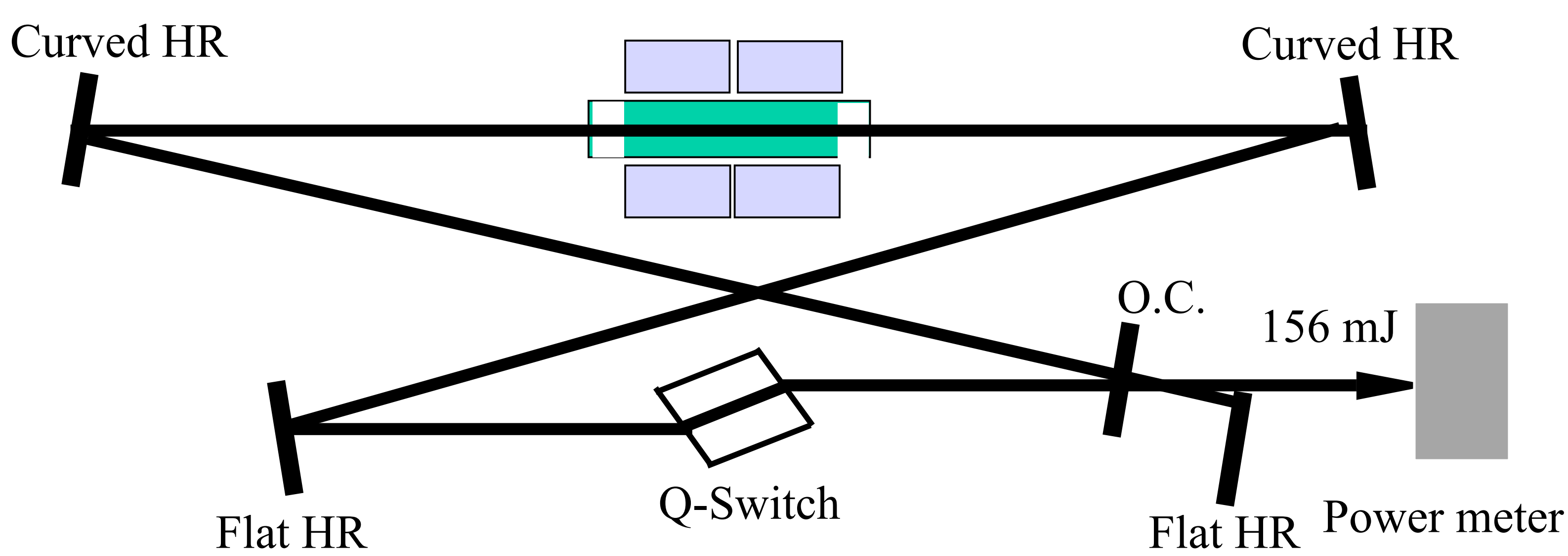
LDAs & laser rod conductively cooled

Diode-pumped Laser Oscillator Head (2003)



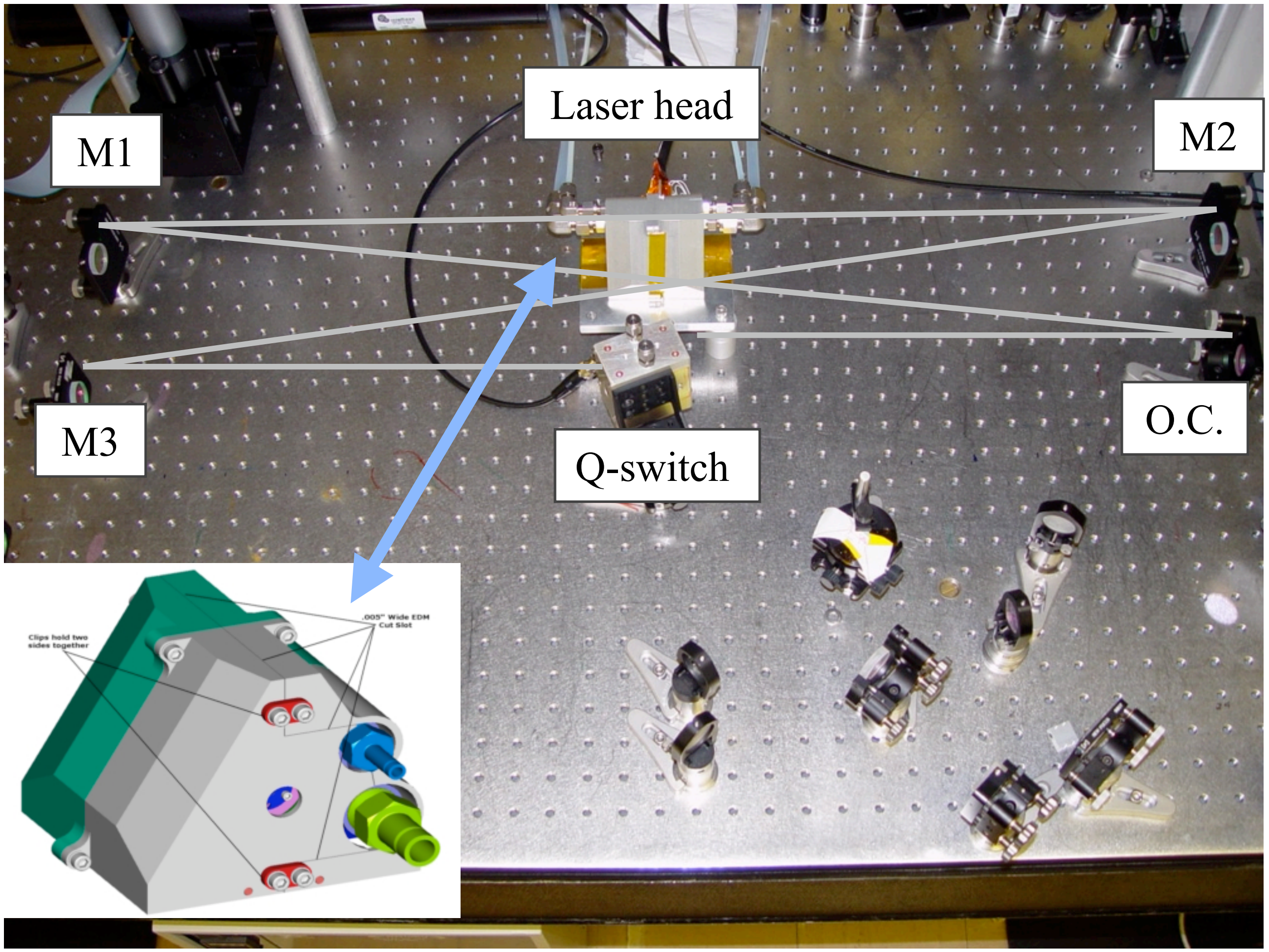


Ho: Tm: LuLF Laser Oscillator (2003)

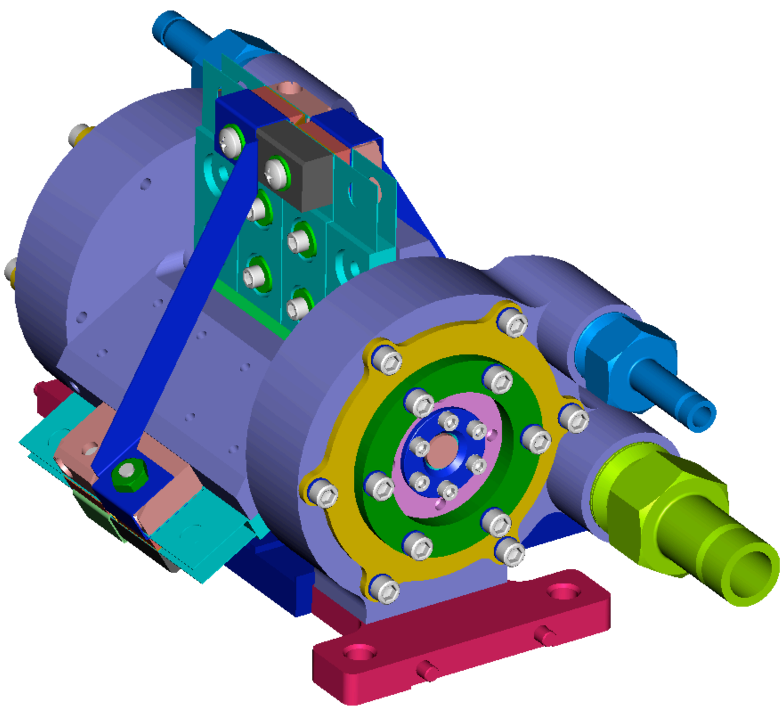


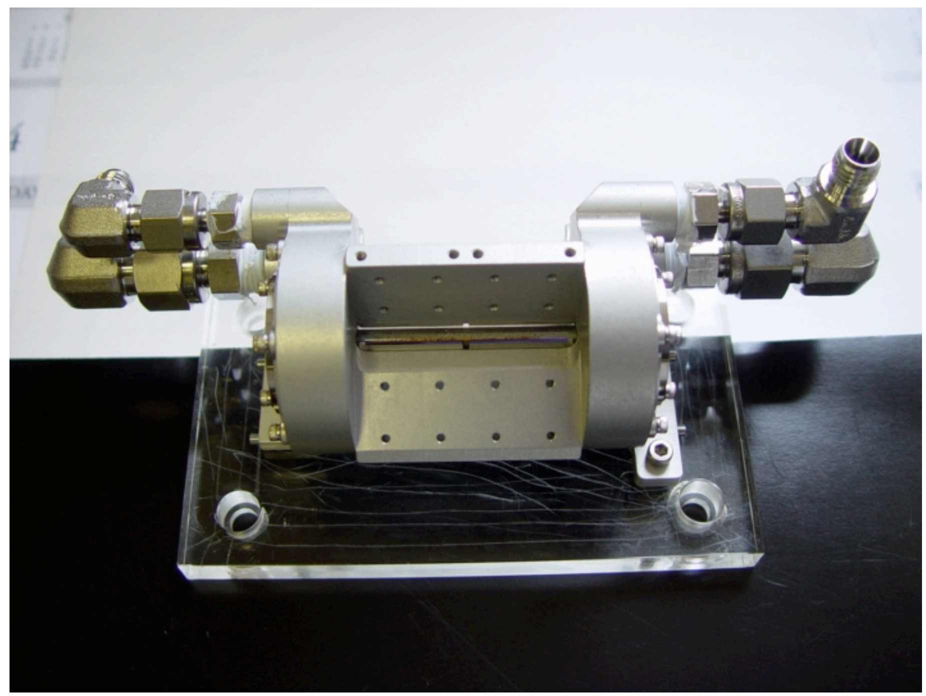
Output pulse energy: 156 mJ @ pump energy of 3.7 J
Larger mode volume in rod; uniform beam size in cavity; record energy, oscillator only

Diode-pumped Laser Oscillator (Ring Cavity) (2003)



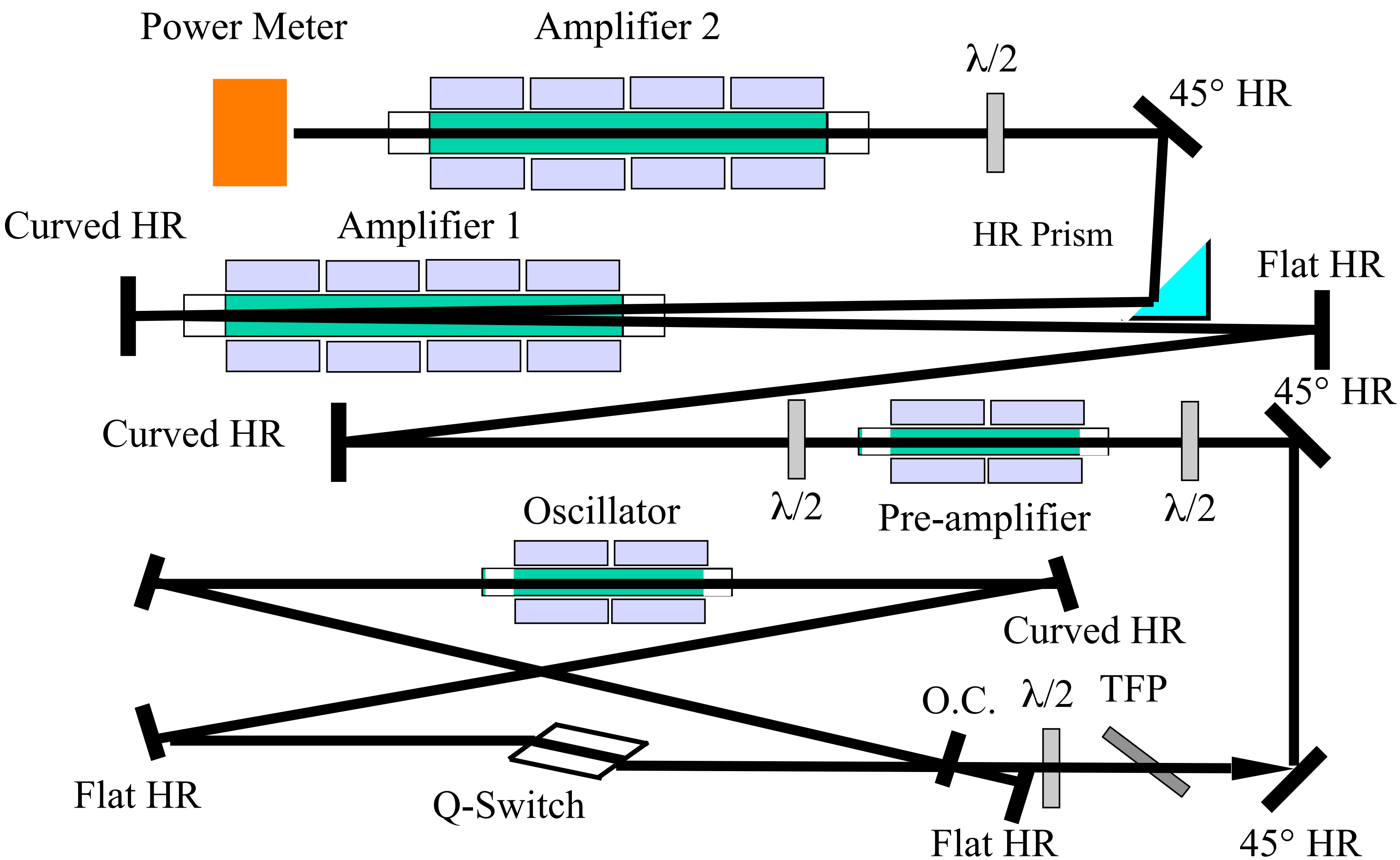
Newly Designed Laser Amplifier Heads (2004)



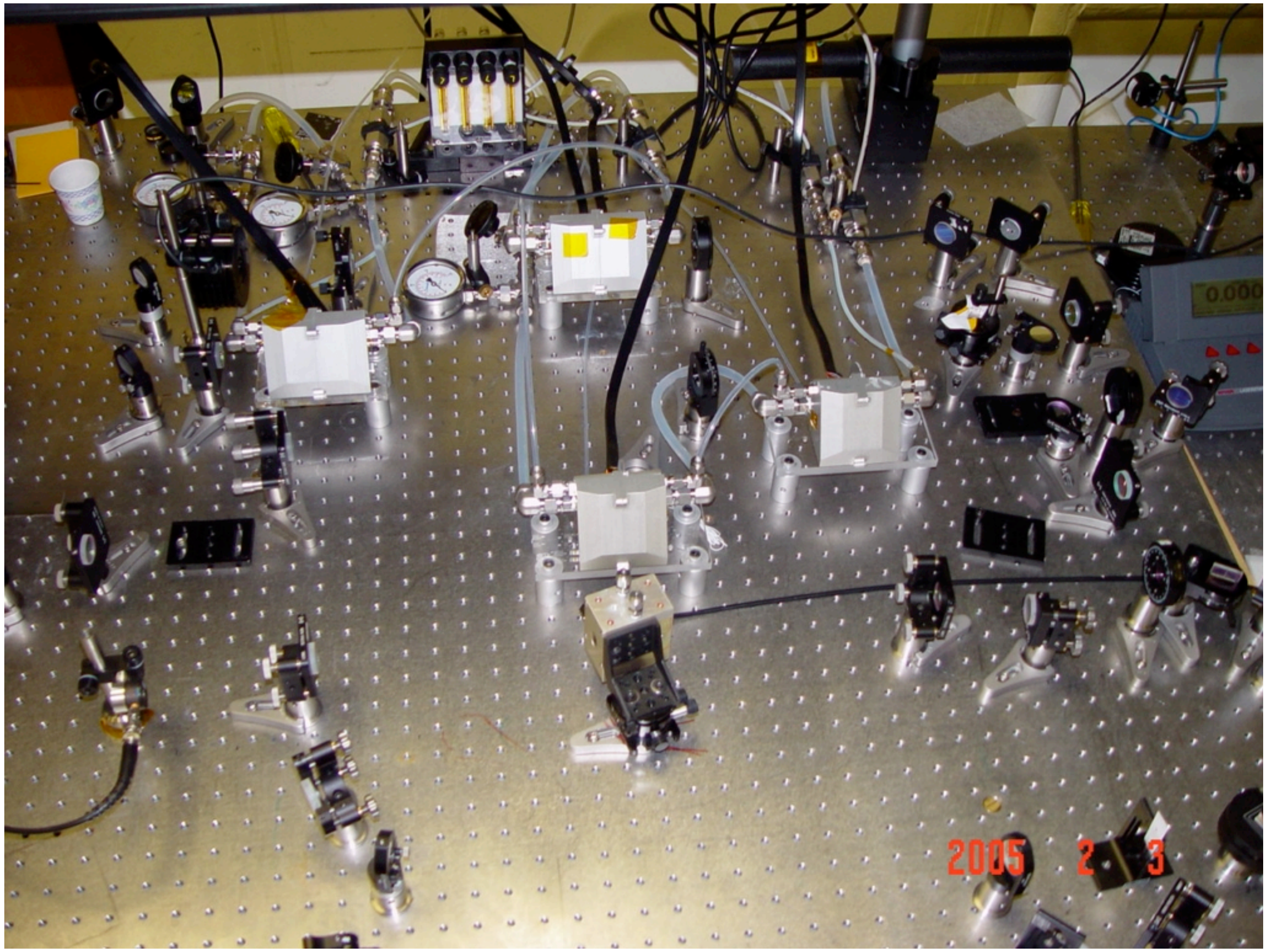


4 LDAs side by side instead of 2 as in oscillator

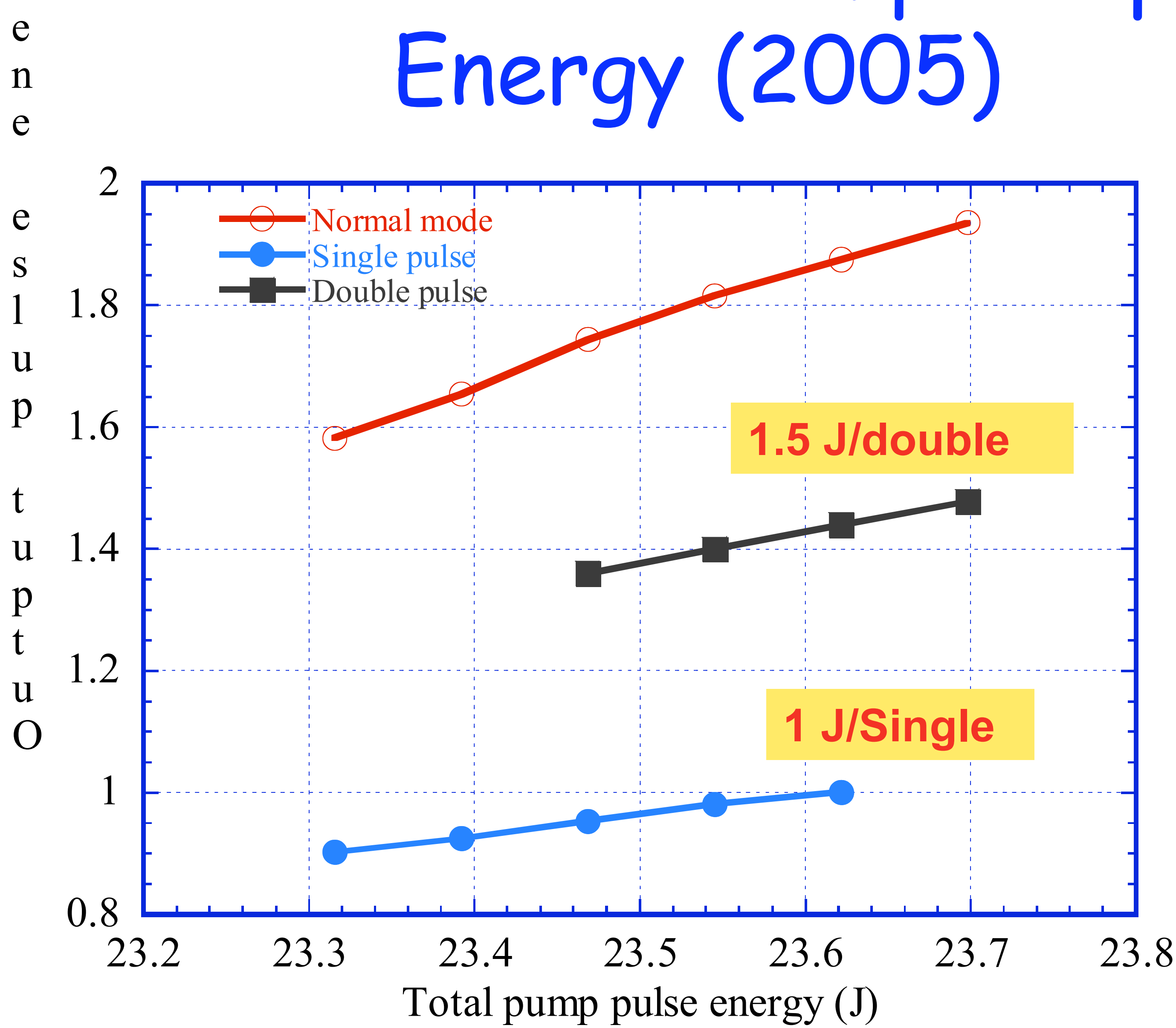
Tm:Ho:LuLF Laser Oscillator and Amplifiers (2004-5)



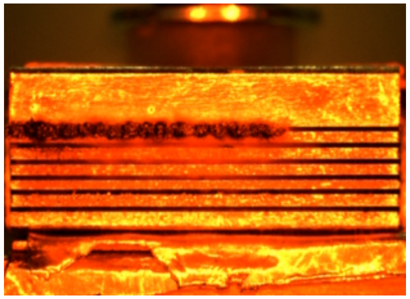
LaRC 2-micron Solid State Laser (2004-5)



2-Micron Osc/Amp Output Energy (2005)



Advancement and Risk Reduction of Laser Diodes



Objectives

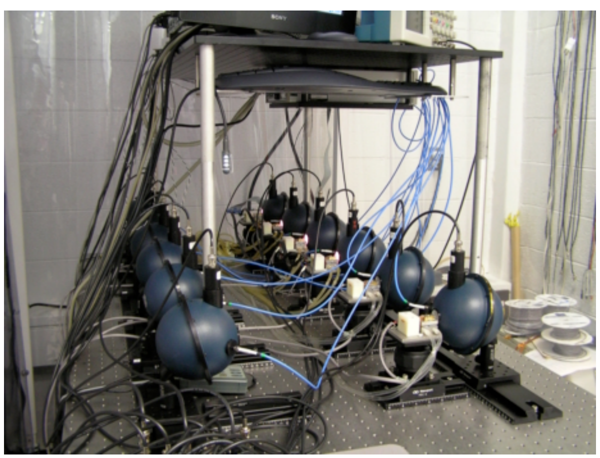
- Develop state-of-the-art characterization and life-time test facility and address laser diode issues *emphasizing 792 nm arrays*:
  - Limited reliability and lifetime
  - Lack of statistical and analytical bases for performance and lifetime prediction
  - Limited commercial availability
- Develop advanced laser diode array (LDA) architectures with improved efficiency and reliability
- Develop Reliability and Space-Qualification Standards and Test Procedures

Advancement and Risk Reduction of Laser Diodes

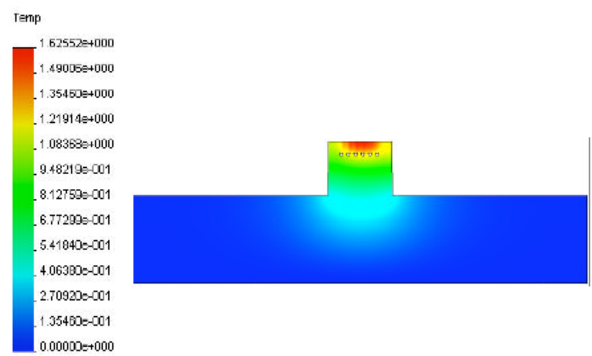
FY '04 Accomplishments

- Began Lifetime Testing of Standard Package LDAs
- Expanded lifetime test station to measure 12 LDAs simultaneously
- Assembled a stand-alone characterization setup for high-quantity routine LDA measurements
- Developed a new G-package design with substantial reduction in solder thickness resulting in better thermal properties and improved reliability
- Completed thermal modeling of both standard and modified G-packages
- Began fabrication of 3 different types of advanced submount materials
- Completed fabrication of the first set of carbon composite submount materials
- Established working relationships with 4 major LDA suppliers and initiated discussions with DoD, Penn State Univ, and major aerospace companies

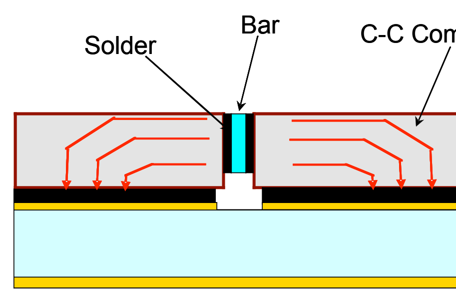
Lifetime Station



Thermal Model of G-6 Package



Advanced LDA Package

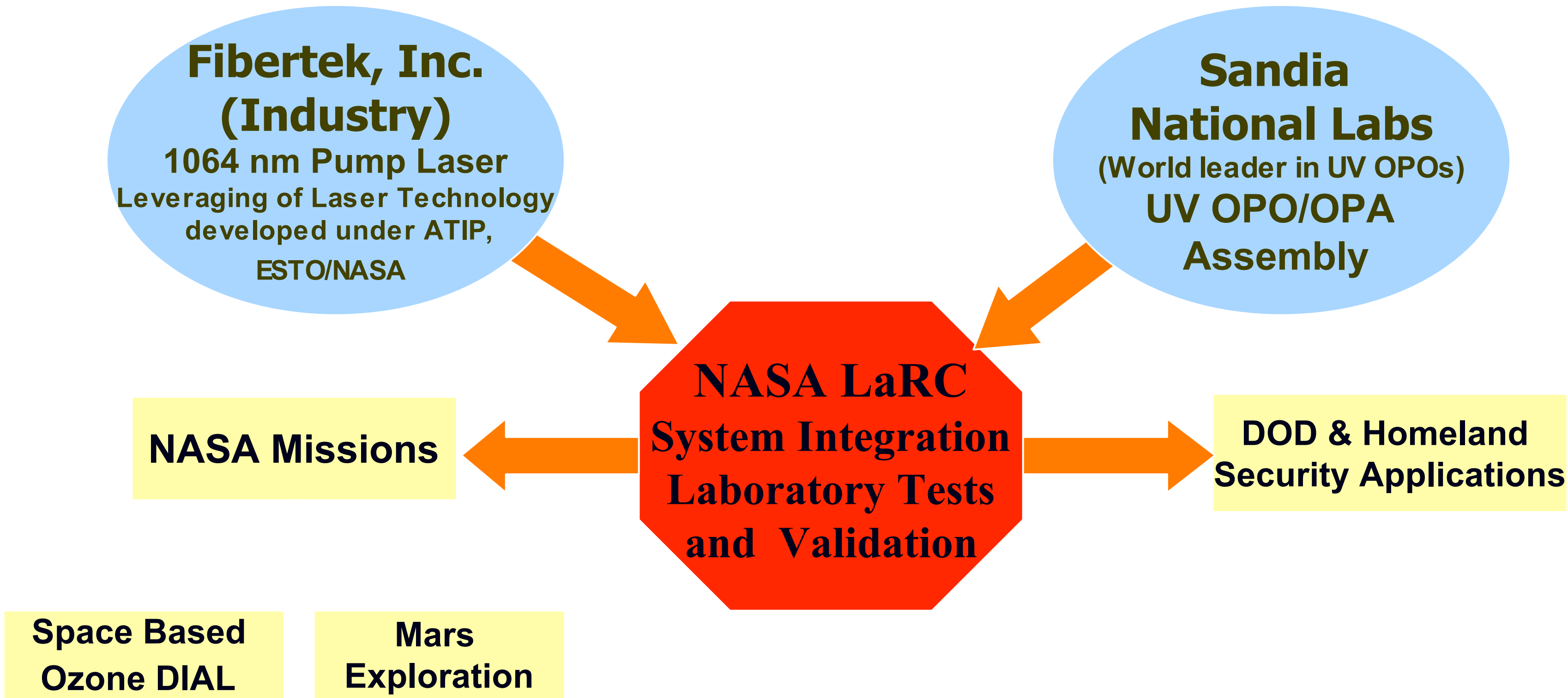


UV Program Objectives

- The objective of the ongoing UV program is to demonstrate a high pulse energy, short pulsed, low PRF and tunable UV transmitter suitable for space based ozone DIAL system development
- The goal is to demonstrate at least 200 mJ/pulse at 10 Hz PRF and around 20 ns pulsewidth
- Initial emphasis is to generate the 320 nm wavelength
- The follow-on plan is to extend the current scheme to generate 308 nm wavelength

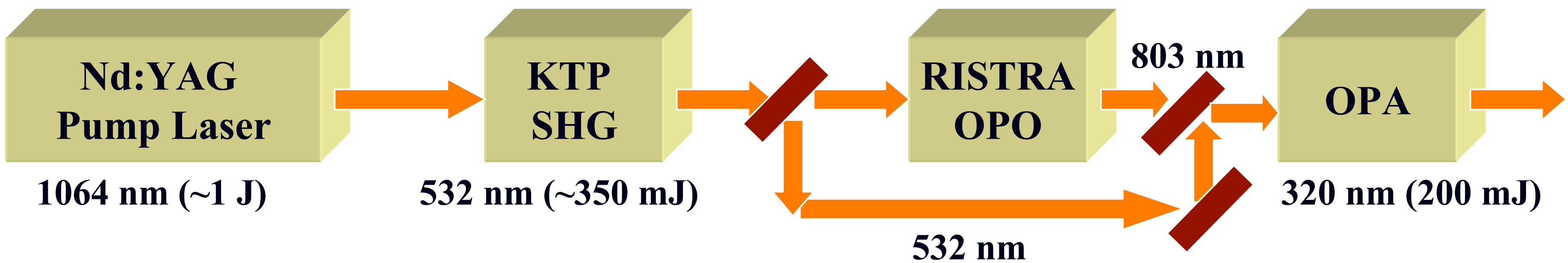
UV Program Path

- Besides internal efforts, NASA LaRC is partnering with industry and National Labs to build a unique multi-functional UV lidar transmitter

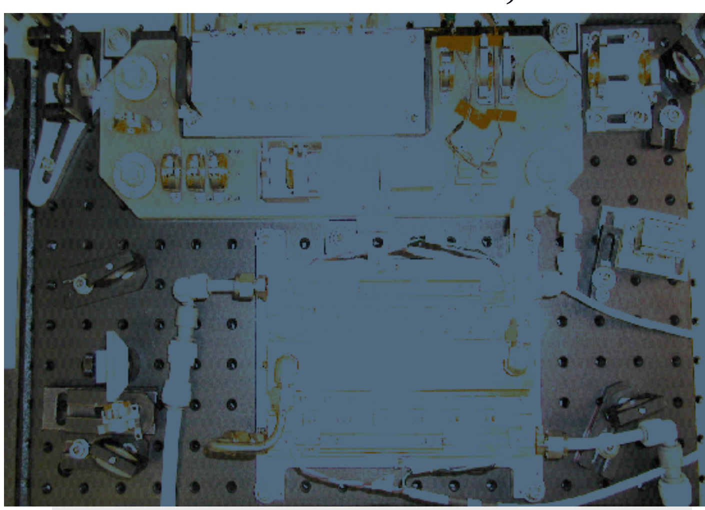


- Thus far, the partnership has yielded significant results

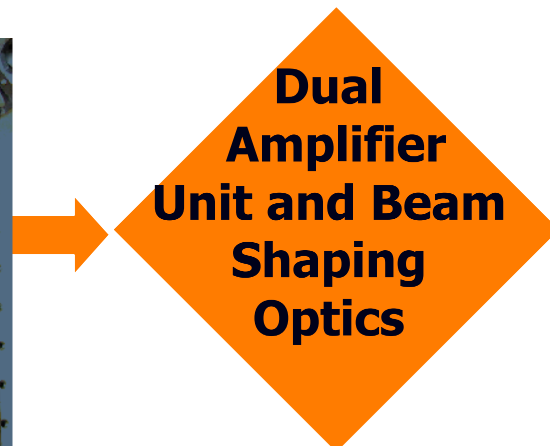
The UV Transmitter Scheme



300 mJ diode pumped Nd:YAG laser from Fibertek, Inc.



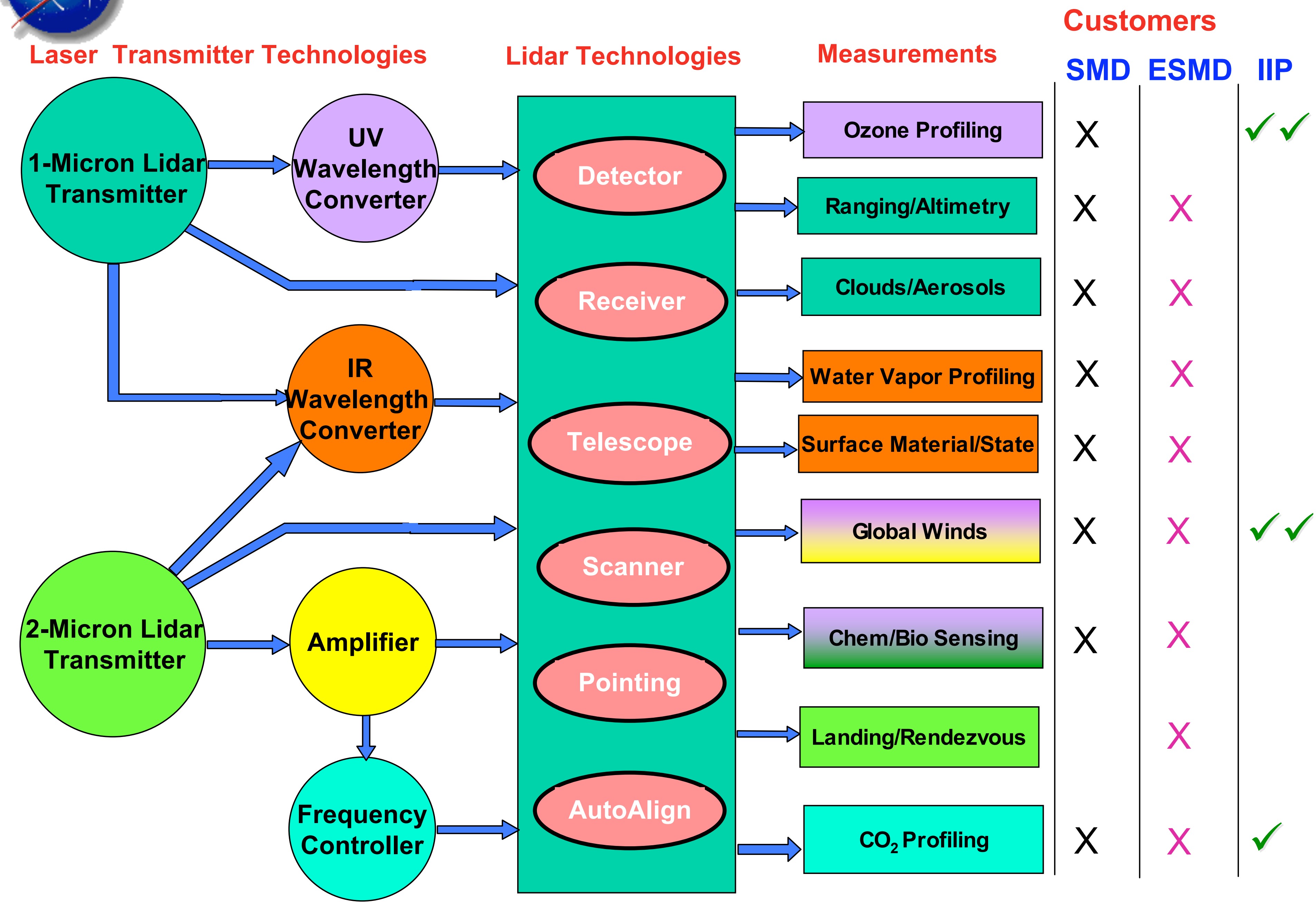
Developed under ATIP funded by ESTO



Laser Upgrade Under Development

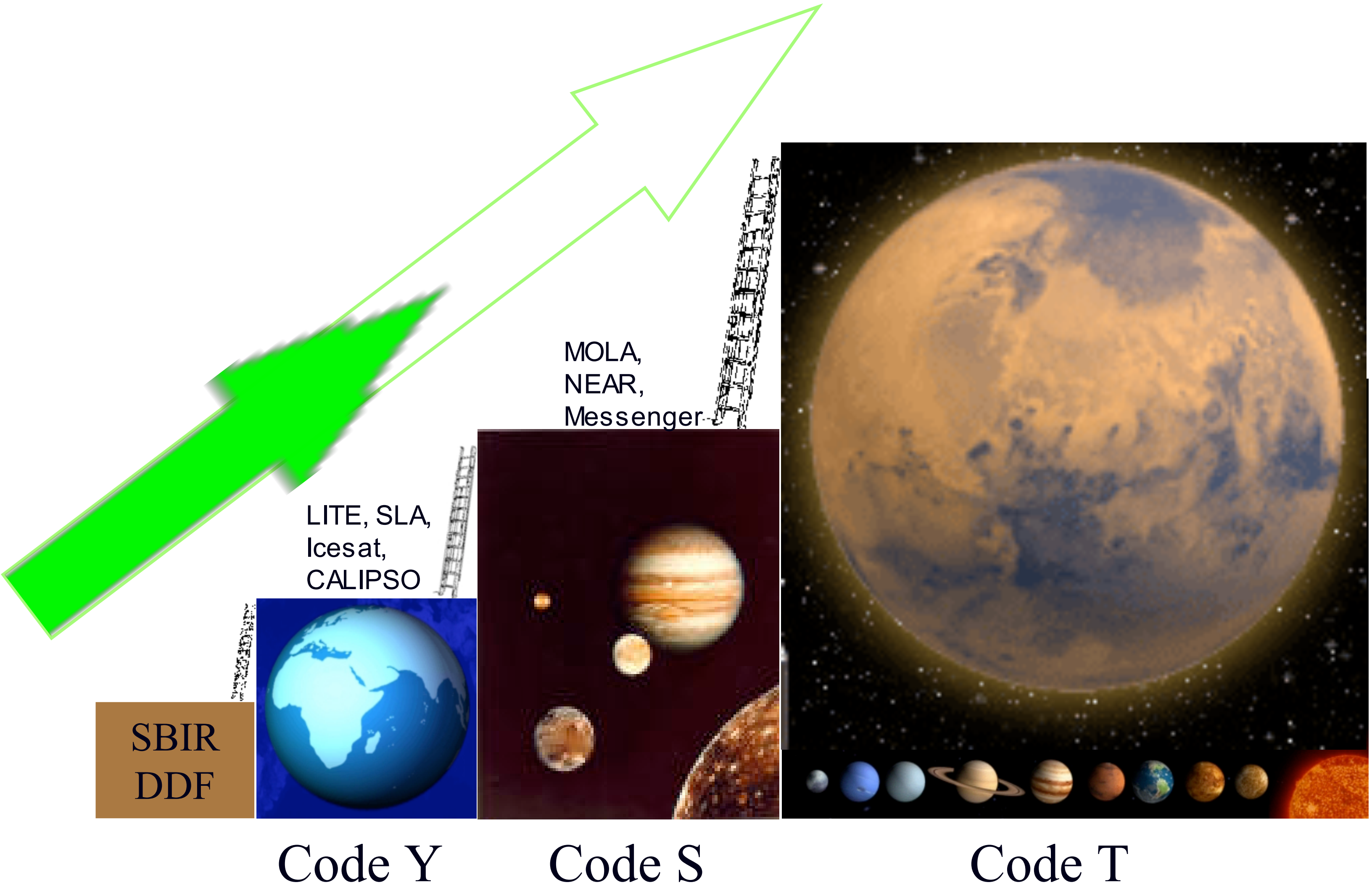
RISTRA UV OPO
From Sandia

Enabling Technology Elements



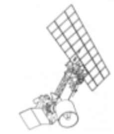
Lidar: Exploration Focus

Taking Advantage Of Years Of Technology Development



LRRP/LLTE: Exploration Focus

2 Lasers, 4 Techniques, Numerous Measurements



2 MICRON LASER

Key Technologies in Common

- Pump Laser Diode Arrays
- Optics Damage
- Frequency Control
- Beam Quality
- Electrical Efficiency
- Heat Removal
- Ruggedness
- Lifetime
- Contamination Tolerance
- Radiation Tolerance

1 MICRON LASER

2.05 micron → COHERENT DOPPLER; DIAL

1.06 micron → X3 → 0.355 → DIRECT DOPPLER; X2 → 0.532 → BASIC

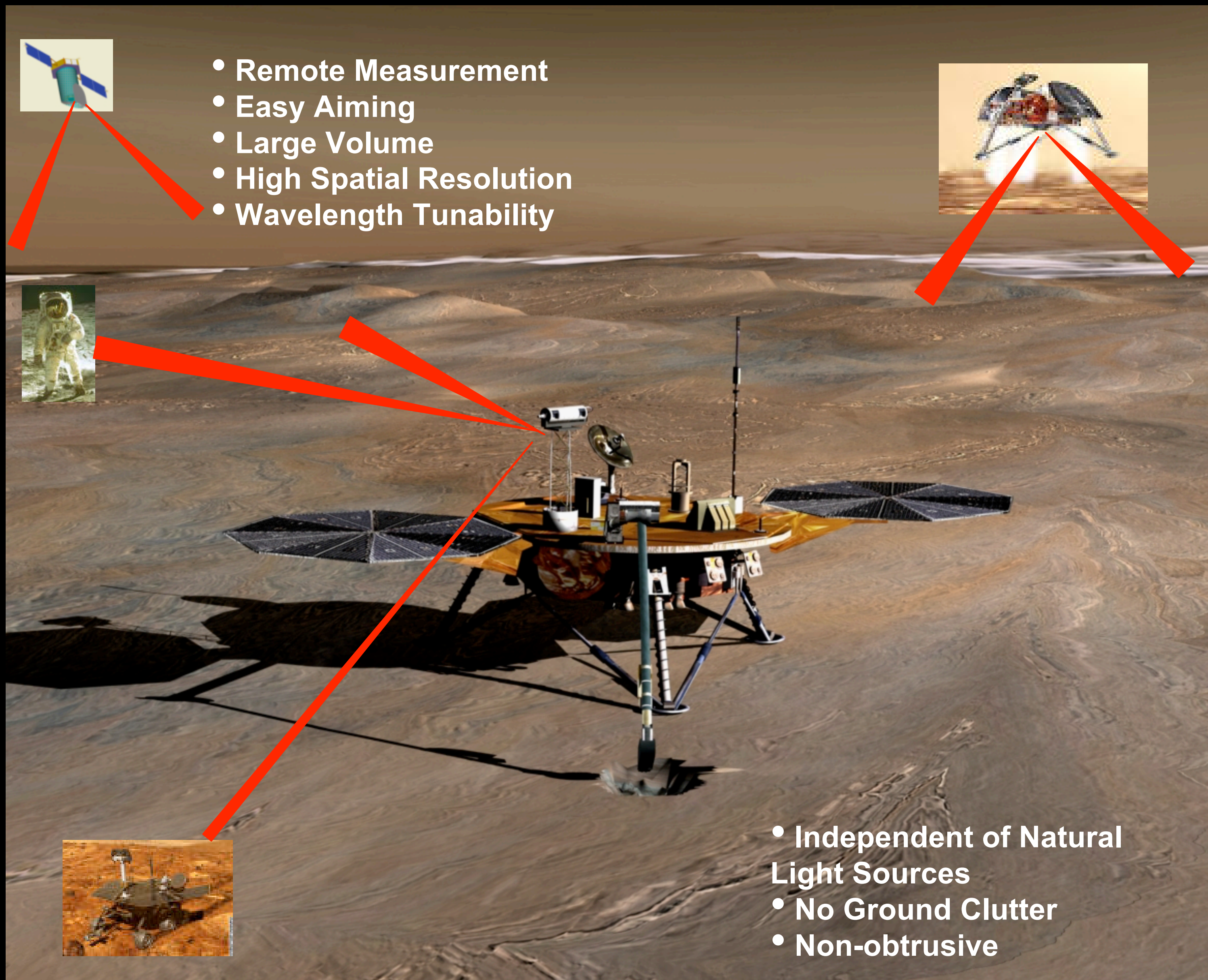
Planetary Orbit
- Wind Profiles
- Water Vapor Profiles
- CO_2 Profiles
- Aerosol Profiles
- Altimetry

Descent
- Range
- Velocity
- Attitude/Rotation
- Wind Conditions
- Hazard Detection

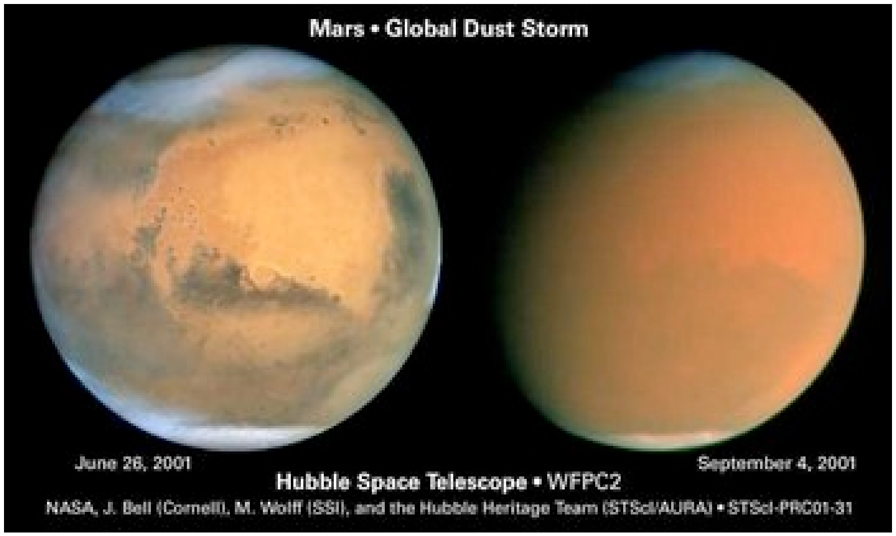
Rendezvous
- Range
- Velocity
- Attitude/Rotation

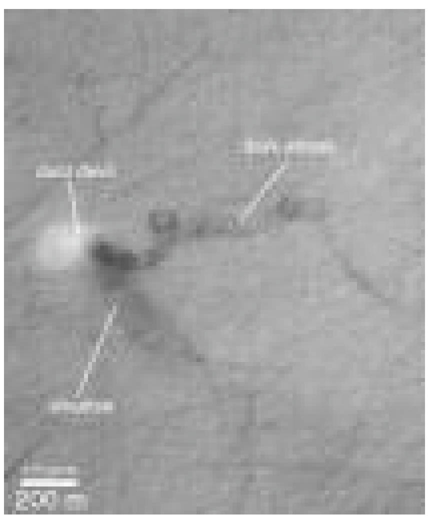
Lander/Rover
- Wind, Water Vapor
- CO_2, Aerosols
- Ranging
- Imaging
- Mineralogy
- Biosensing

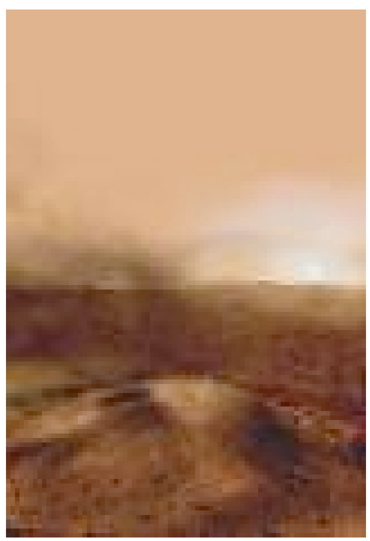
Laser/Lidar Active Optical Remote Sensing

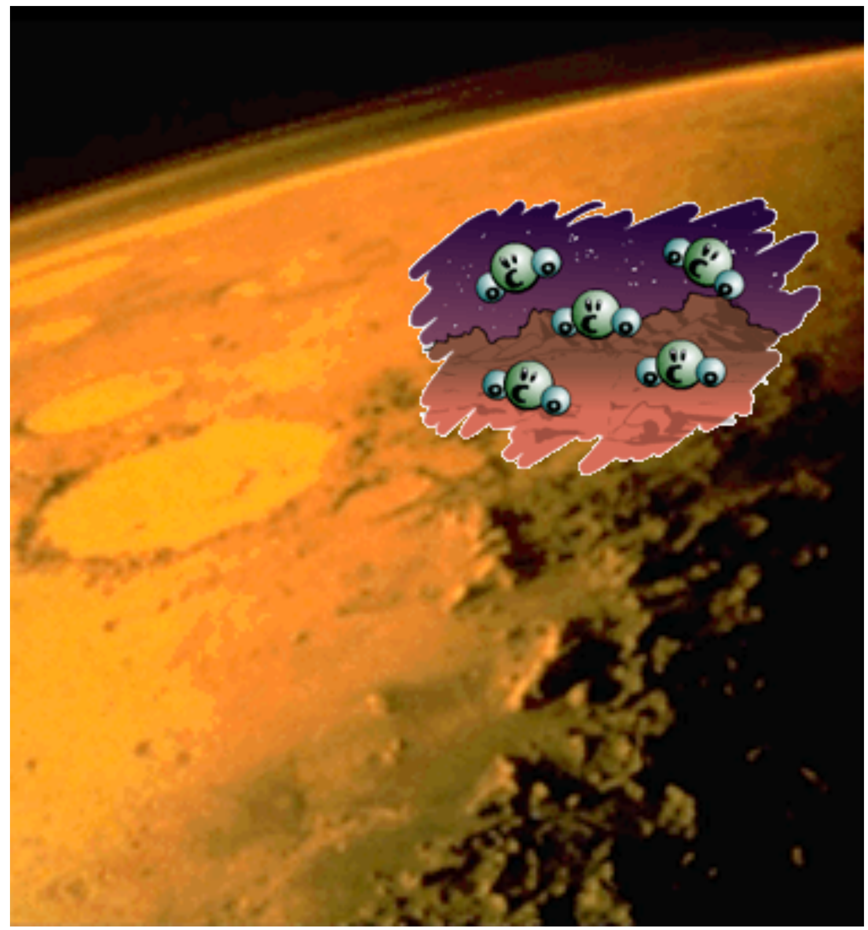


LLTE: Mars Orbiting Lidar









Motivation

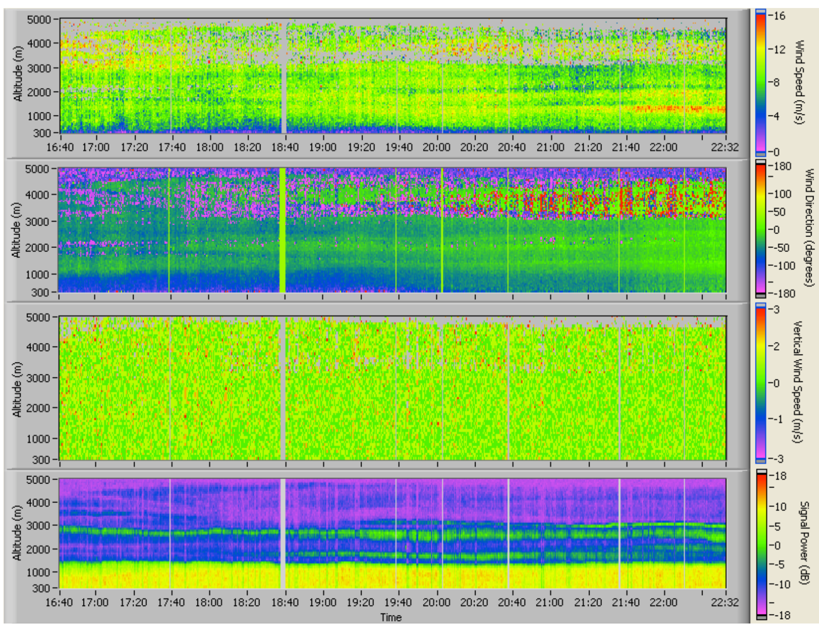
- Provide an instrument to profile Martian atmosphere: wind (by Doppler shift), atmospheric density (by DIAL of CO_2), and aerosol density (by backscatter intensity).
- Measurement of three parameters can be made with single orbiting 2μm lidar.
- Unknowns of Martian atmosphere have significant impacts on future exploration:

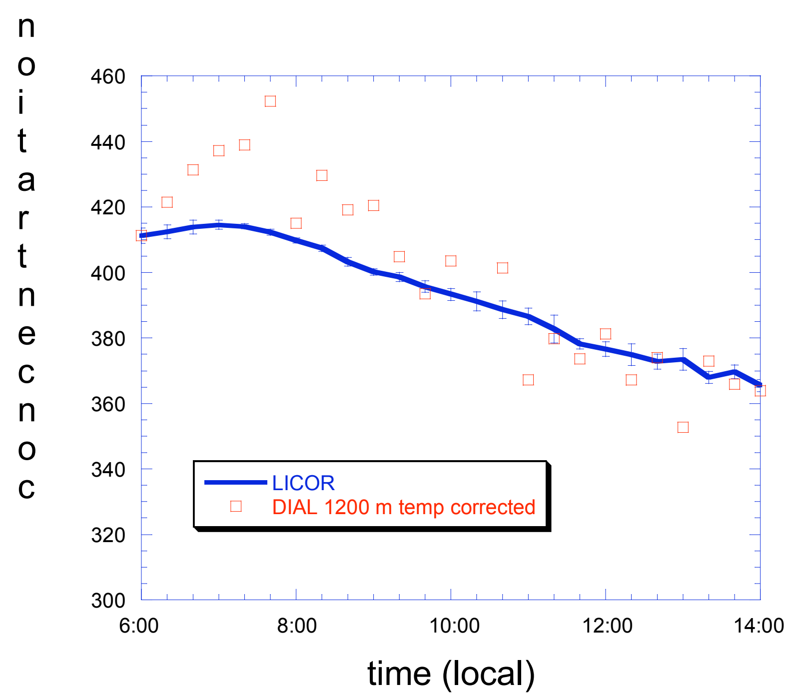
"**orbital remote-sensing weather station** is recommended to obtain vertical profiles of V, T, and ρ around the globe with high temporal and spatial resolution, particularly emphasizing heights between 0-20 Km and 30-60 Km."*

* From NASA draft report "An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars."

Technology Heritage

- LaRC, primarily under LRRP, has developed technology to enable lidar measurements from Mars orbit: high-energy lasers, conductive cooling, single-frequency spectrum, precise wavelength control, and optimized heterodyne detectors.
- Proof-of-concept demonstration has been made of coherent DIAL lidar system for simultaneous wind and CO_2 measurement:





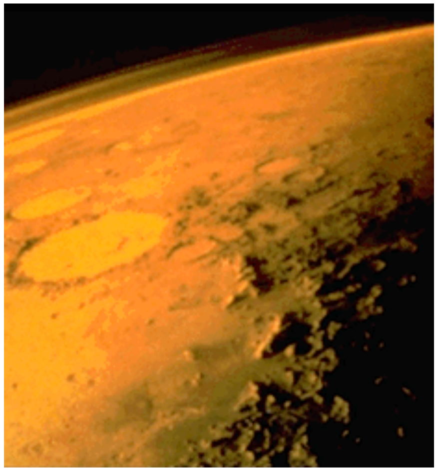
Approach

- **Phase 1: 1-year duration (FY 2005)**
  – Create model of lidar performance in Mars atmosphere (partner SWA)
  – System designs and trade studies
  – Technology assessment.

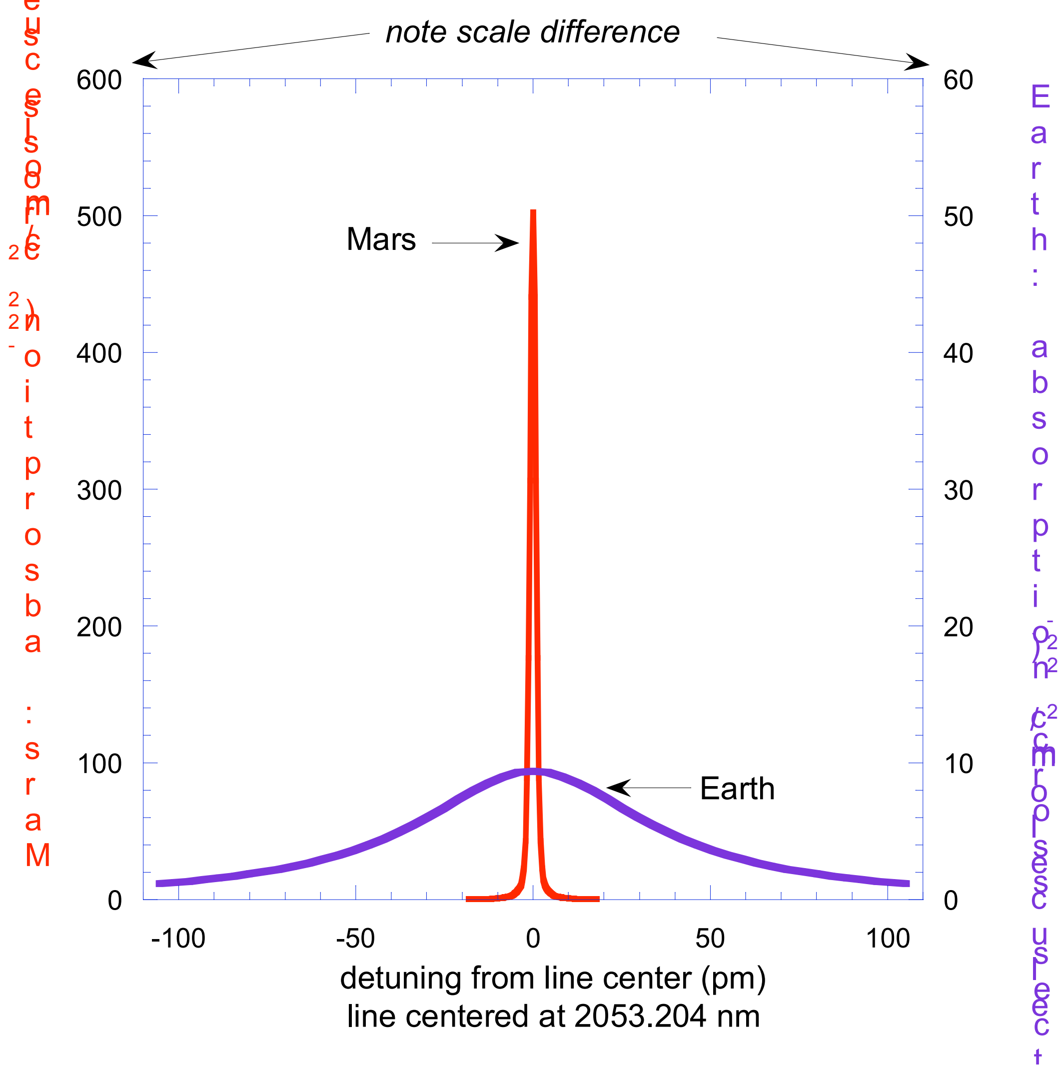
- **Phase 2: 2-year duration**
  – Build breadboard prototype lidar.
  – Calibrate CO_2 precision with spectroscopy
  – Test and validate with atmospheric measurements correlated with other sensors.

A Rough Calculation

- Extrapolating current understanding of Earth wind measurement capabililty, and
- Extrapolating on detection of dust devils on Mars by Mars Orbiting Laser Altimeter (MOLA)
- Wind measurements are easier on Mars than Earth. A relatively modest lidar would do the job on Mars:
  - **Lower orbit height**
  - **More aerosols/dust**
  - **No strict requirements (yet)**



System Design--CO_2 Line Selection

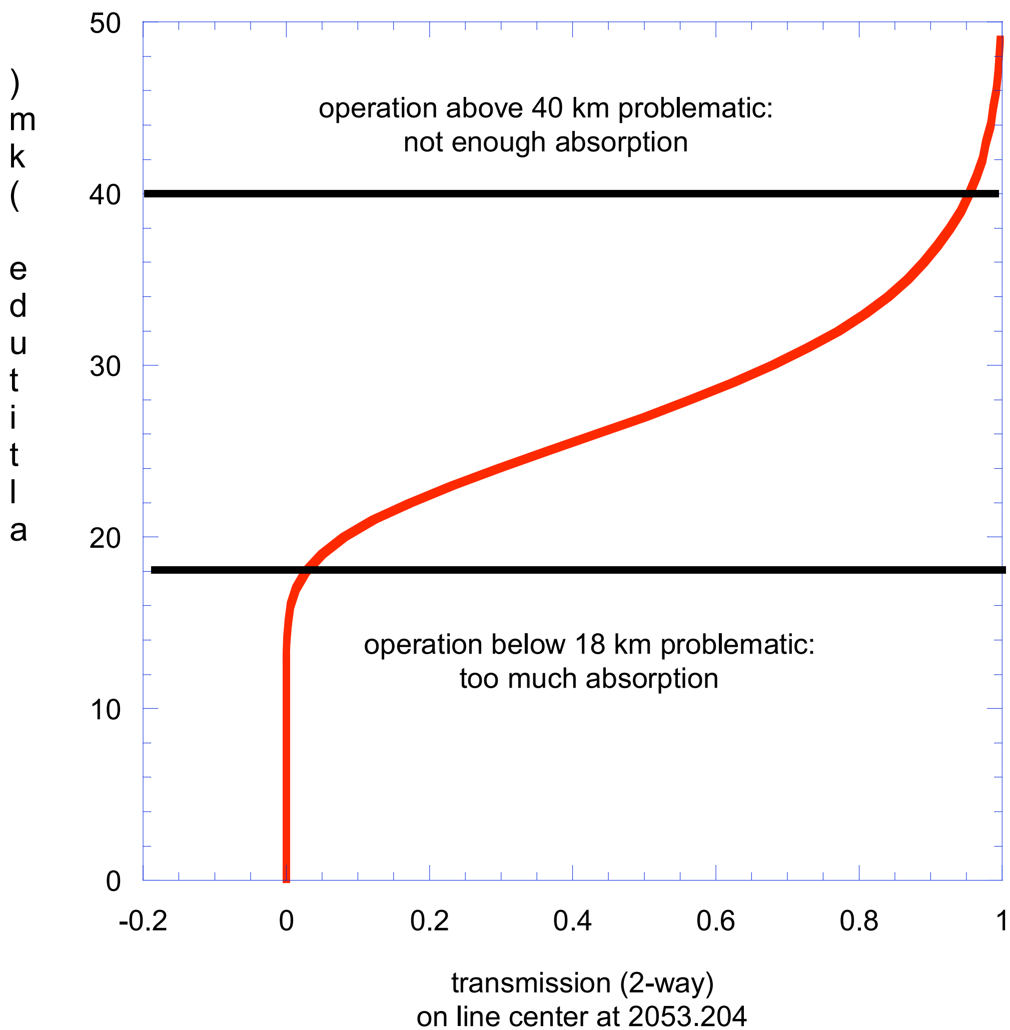


Line centered at 2053.204 nm selected for:

- good laser operation
- insensitivity to temp.
- line strength
- no interference from other gases.

Line is "tall and skinny" compared to Earth because of much lower pressure on Mars.

Transmission on Line Center



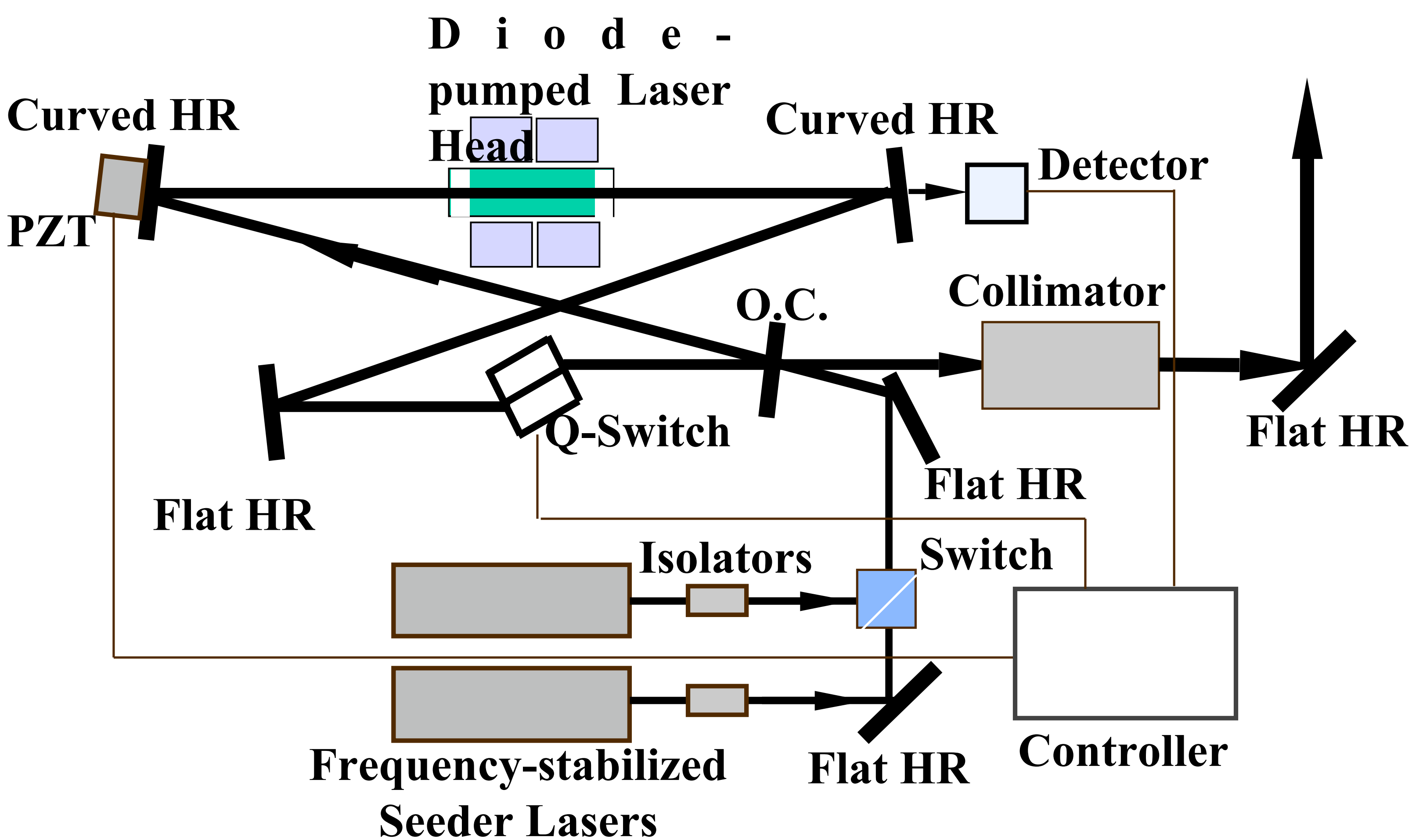
Line strength gives measurements at high altitudes, where density measurements are desired.

Altitude of optimum operation can be tailored:

- choose neighboring line of different strength (stronger and weaker are available)
- tune laser off line center
- exploit Doppler shift

Singh 2005, ESTO-05

Ho:Tm:LuLF Laser Oscillator (Ring Cavity)



MOL Conclusions

- Characterization of atmosphere of Mars shown to be critical for exploration. Wind, density, and dust are needed measurements.
- 2-μm coherent DIAL is promising for wind, CO_2 concentration, and dust profiling with a single instrument.
- Performance model under development.
- Accessible absorption lines are well suited to CO_2 measurements in the upper atmosphere, where measurements are desired.
- Most of lidar technology needed has been demonstrated in lab and system testbed. Remaining technology of rapid wavelength switching is being addressed.

Laser Risk Reduction Program- Collaborations

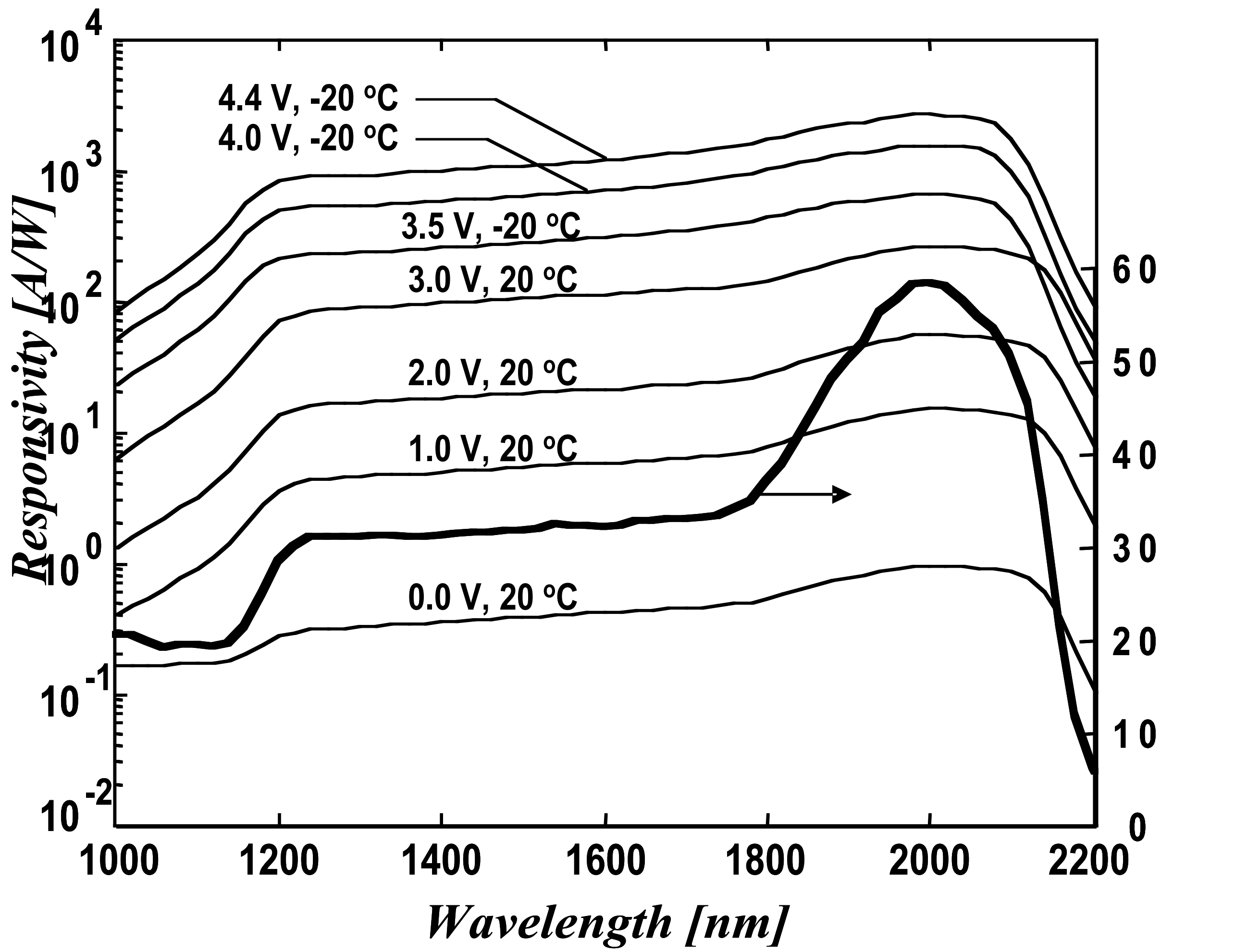
Backup Charts

Custom-designed 2-micron detector's performances

Goals/Actual Performance

Detector Parameter	DIAL Goals	Actual Performance	Units
Responsivity	50	2650	A/W
Quantum Efficiency	= 50	58	%
Noise Equivalent Power	$< 2\times10^{-14}$	1.86×10^{-14}	W/Hz?
Operating Temperature	– 20	120 to –196	°C
Bandwidth	10	430	MHz

Spectral Response and Quantum Efficiency of ALGAS/INGAS Phototransistor



Integrated Heterodyne Photoreceiver

Objectives

- Improve Coherent Lidar receiver electronics efficiency by over 3dB.
- Reduce required Local Oscillator (LO) power by about 80% using the dual-balanced detector configuration.
- Integrate all lidar receiver components into a miniature monolithic package.

Impact on Space-Based Doppler Wind Lidar (2J X 12 Hz, 75 cm):

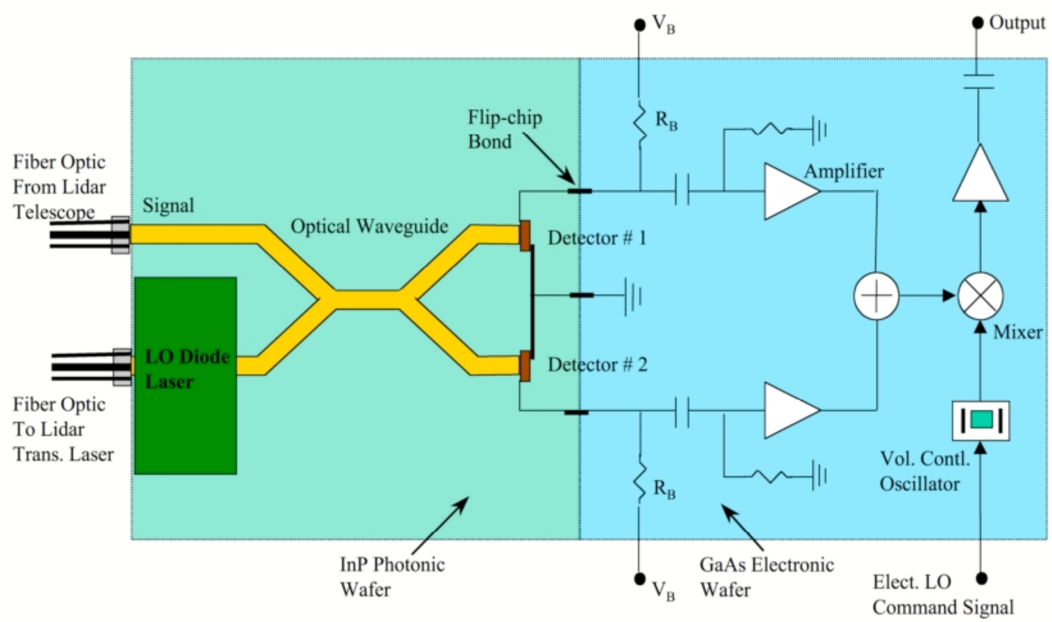
Mass Reduction	***125kg (20%)***
Power Savings	***600W (35%)***

Integrated Heterodyne Photoreceiver

- Dual-Balanced Detector Configuration
- Hybrid package includes all the receiver components:
  - Local Oscillator Diode Laser
  - Optical Mixer
  - Detectors
  - Amplifiers
  - Electronic Interface
- Integrated Opto-Electronic Packaging Technology

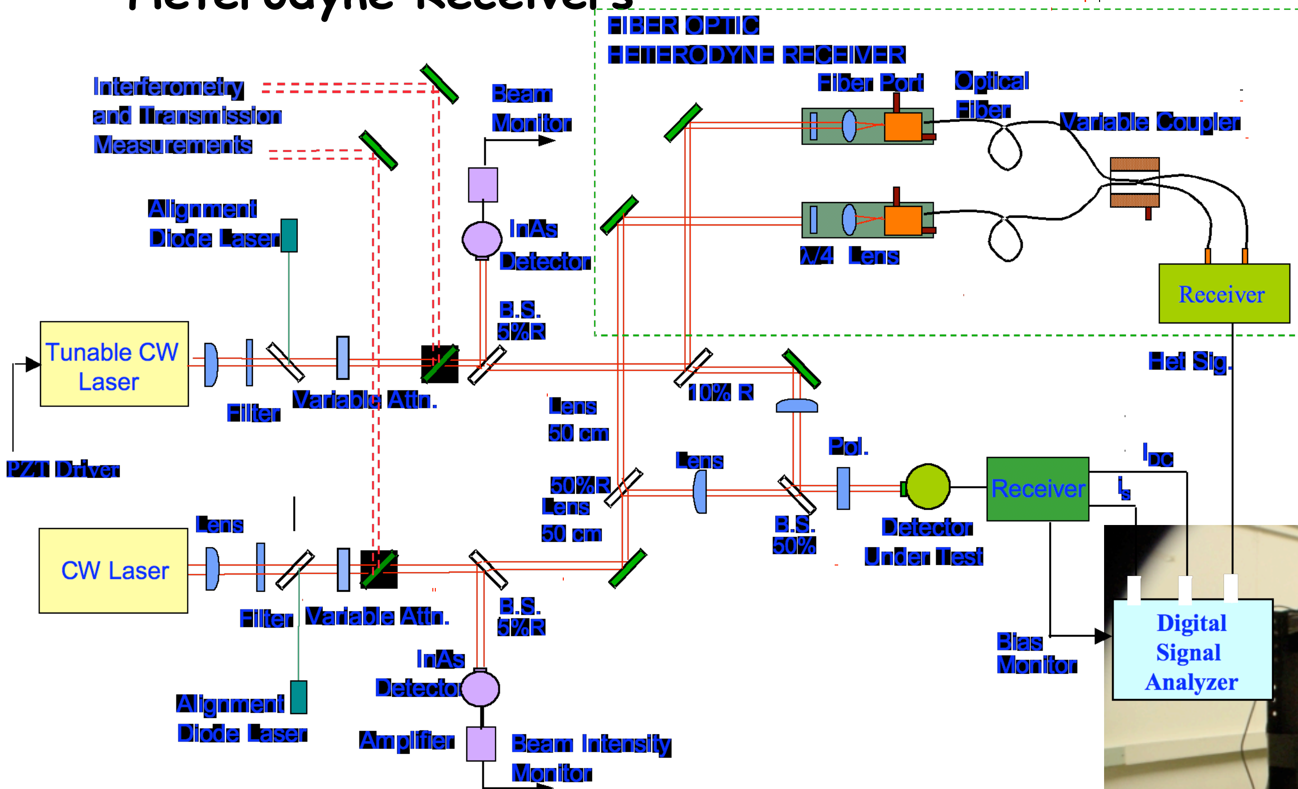
<u>Advantages</u>

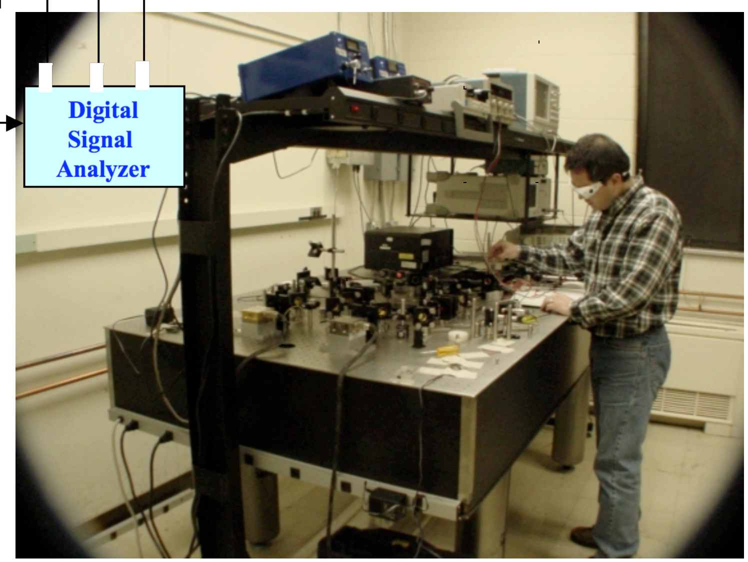
- Improved sensitivity by 3 dB
- Reduced LO power by more than



Lidar Receiver Characterization Facility

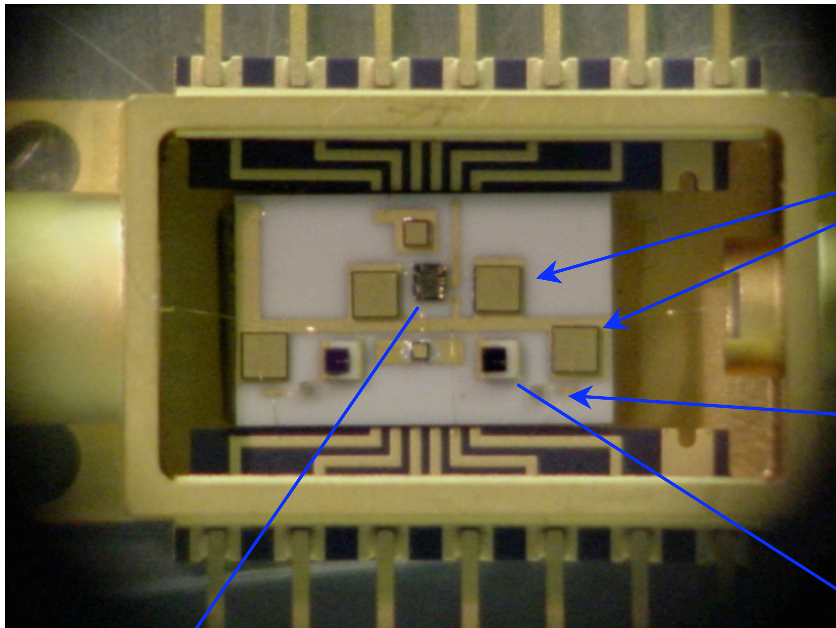
- Capable of fully characterizing 2-micron Detectors and Heterodyne Receivers





Integrated Heterodyne Photoreceiver

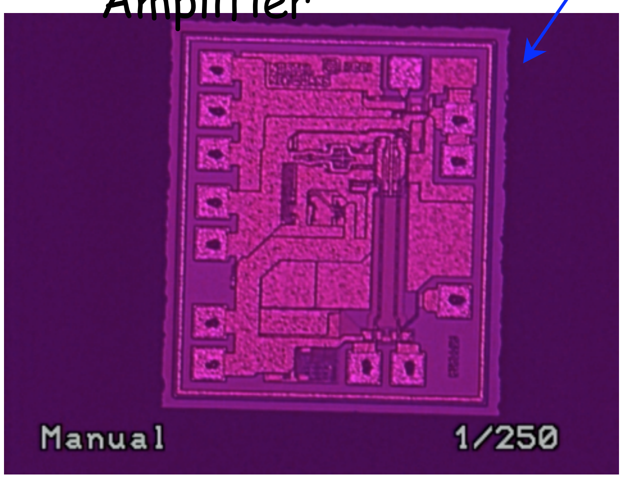
Example of the Receiver Boards fabricated in-house



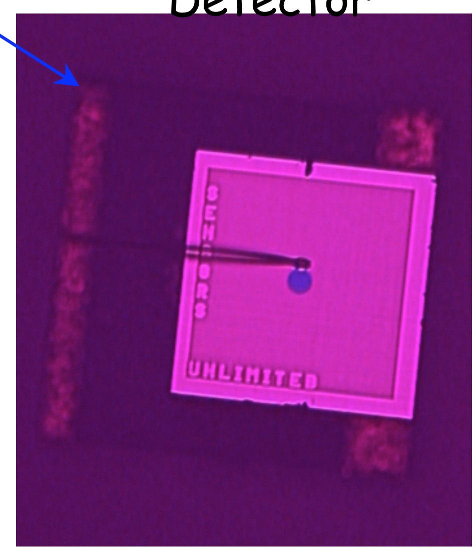
Capacitors

Resistor

Transimpedance Amplifier

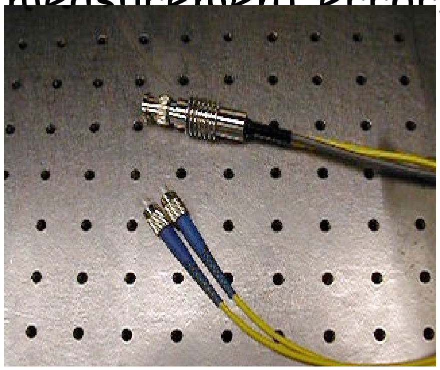


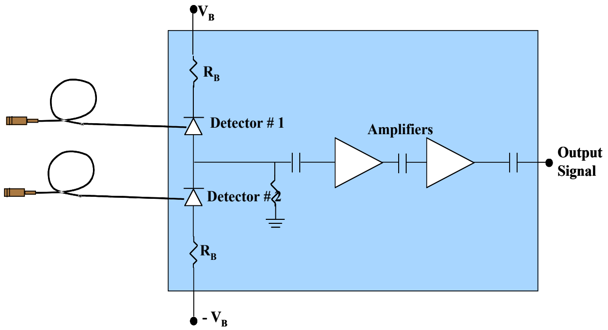
Detector

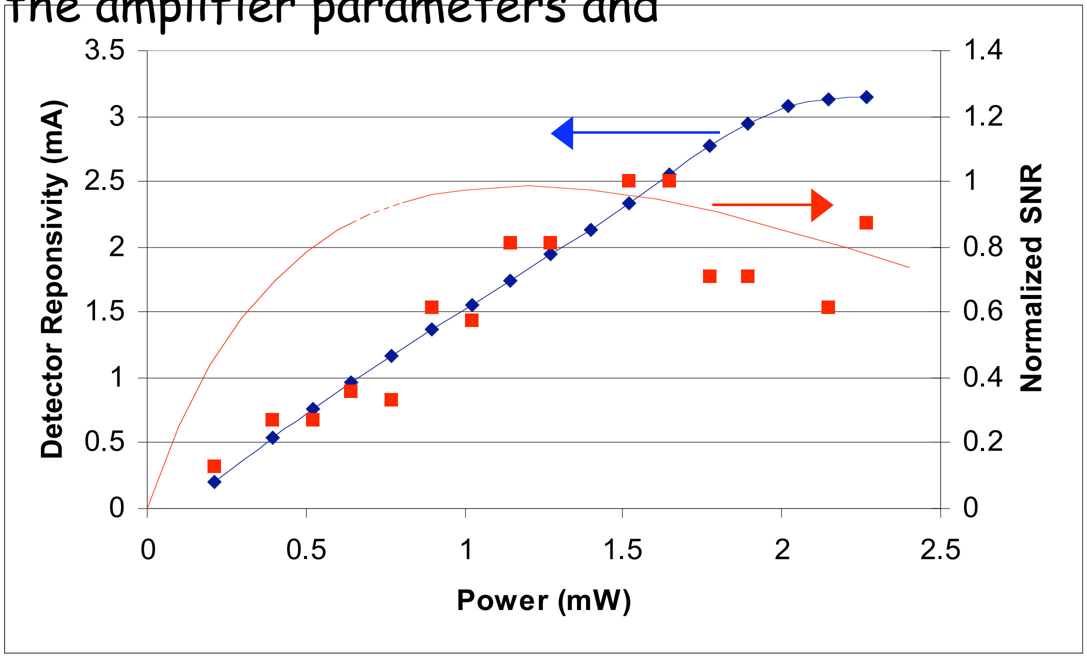


Model Validation Experiment

- Results validate optimum LO power formulation
- Good agreement between theoretical and experimental data
  - –Optimum LO power = 1.5 mW experiment vs. 1.2 mW theory
- Discrepancies between experimental data and model are attributed to lack of accurate knowledge of the amplifier parameters and measurement errors







Exploration Remote Sensing Applications

- Orbiting weather station: air density, dust, winds
- Planet topography
- Lander area mapping
- Landing site selection
- Entry, Descent, and Landing (EDL) velocity, altitude, winds, dust, surface hazard avoidance
- Rover and astronaut warning of winds and dust storms
- Planet surface material composition; mineral content
- Water and water vapor presence and amount
- Atmospheric pressure & content
- Range and composition of interesting objects
- Presence of organic compounds
- Rendezvous range, closing velocity, rotation